ORIGAMI ENGINEERING:
ADVANCED CONVERTING FOR NOVEL PAPER PRODUCTS

by

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Abstract

The recent work has focused to develop a fully automated prototype in order to make products in large quantities. A unique and novel methodology has been developed to create self-folding paper products. This platform technology enables us to create sophisticated complex 3D paper structure from ordinary 2D paper sheet. The self-folding material is composed of pre-cut and creased paper and heat shrinking thermoplastic polymer.

A computational drawing tool is first used to design folds for particular 3D shape then a computer numerical controller cutter with knife at variable pressure is employed to cut paper and the thermoplastic polymer. The cut paper and thermoplastic polymer can be attached together by a large number of polymeric materials and several means of attaching polymer-paper have been explored. The effect of various polymer-paper attachments including chemical adhesion, stitching and welding was studied. Heat welding procedure was quite successful and it showed to be promising technique to make a strong polymer-paper bond. An experimental device was made and a series of experiments were conducted to reveal the significant factors, their effective range, and their impact on the paper-polymer bond strength. The effect of pressure, temperature, welding attachment area and, thickness of paper on the paper-polymer bond strength were determined and a database of strength attachments with an effective factors variation was collected.

First, our in-house developed servo-robot for cutting was assisted with automatic welding system and then a large flatbed cutter has been used and functionally changed to perform cutting, creasing and adhering paper and plastic in one step. The effect of significant factors such as attachment distance to fold line, heating temperature and paper thickness on the folding angle has been studied and discussed in chapter 4. Several examples of folded decorative and industrial products have been developed using this technique and introduced in chapter 5.

Preface

This dissertation is an original intellectual product of the author, Ata Sina with the guidance of his supervisors, Dr. James Olson and Dr. Mark Marinez. The Arduino code and the processing code used in appendix C and D, originally written by Giles Fernandes.

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Acknowledgments

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Finally, I would like to thank the Natural Science and Engineering Research Council of Canada (NSERC) and all members of Green Fiber Networks (GFN) society for their help and support.

Dedication

To Thomas A. Harris,

the author of "I'm OK, You're OK",

whom I got to know myself better by reading his fascinating book.

Chapter 1 - Introduction

Folding is considered to be a common process in our daily life. There are a wide range of methods including napkin folding, gift wrapping, paper speaker, paper lamp, box folding, car airbag deployment, and packaging; technological applications include protein folding [1], nanoscale DNA-based objects [2,3], solar panels for space deployment [4,5], architectural folding [6], and flexible medical stents [7]. All the macroscopic and microscopic levels of folding, in different applications, are obtained through this process. By adopting the aforementioned folding methods, this procedure can be used to produce various functional ultra-lightweight and incredibly strong paper structures. All the macroscopic and microscopic levels of folding in different applications are obtained through the paper folding process. Different paper folding techniques can be employed for specific materials, which require knowledge of the material properties, the fabrication process, and constructability. There are also primitive techniques used in paper manipulation to form 3D structures which include paper cutting, curving, shaping, and folding. All the basic techniques of folding paper can be considered to be similar to several forms of origami folds. Origami (formed from "Ori" meaning folding and "Kami" meaning paper) is the traditional Japanese art of folding. It introduces folding techniques for two-dimensional sheets of paper (or fabric, cardboard, and metal) into a variety of three-dimensional forms, without the need for cutting or stretching. Origami originated in Japan during the 17th Century and gained popularity in China and Korea where it then spread to Germany, Spain, and Italy. The art of origami has advanced in the last few decades and evolved to become a scientific method [8, 9].

The field of flat origami has been studied and developed mathematically by origamists', such as Robert Lang, to describe the laws of origami, and it has been simulated using computational techniques [10]. All origami developments have led to numerous industrial applications which helped to solve technological problems such as airbag folding, which was discovered by Lang in cooperation with the company EASi [11], [12]. Since any flat material can be folded, the implementation of origami designs is only possible if the sheet material can hold a crease. Paper can be employed to produce a huge range of origami products and is considered to be a cheap, lightweight and sustainable material [13]-[16]. Producing complicated origami patterns, which consist of multiple folds, is a time-consuming process and it requires skills and experience in order to do it properly, although, some manufacturing techniques have been used to form the paper based on origami patterns by using advanced machines. For example, a novel approach for a continuous folding process was developed by passing sheet material through a set of rollers to form the desired folded pattern [17]. However, this and other similar methods are easier than the traditional forming process, but there are still other more popular, low energy consuming folding techniques which can form paper into a wide range of paper products. On the other hand, there is a huge shift in the producers' and consumers' roles so that consumers become innovators. Only a few decades ago, a trend toward end-user participation began in design [18], [19]. Technological advancements have allowed us to use new material, as well as, significantly computer-aided and publishing software that have lowered the time, effort, and money needed to support users who make and fold their own paper products. Another Japanese term for folding paper is kirigami. This is a variation of origami which includes paper cutting within its design.

Several studies have been carried out to produce a low energy consumption paper folding technique which allows users to form their own paper products. The main idea is to utilize an external driving force, such as a thermal actuator or electrical actuator, in order to fold paper based on origami patterns, while providing useful paper structures as a 'green' and sustainable product. In the following literature review section, I will present some of the similar works done for the relevant purposes leading up to my novel technique:

1.1 Molding

A group of UBC Physics students (Jose Luis Lopez, Julian Fong, and James Simard) have studied and created a molding method to fold paper. This method requires using plastic molds to form the paper. For each individual origami pattern, a plastic mold was created by using a 3D printer. The molds were cast into two main pieces to help hold the paper in between and form it while they are being fixed on each other.

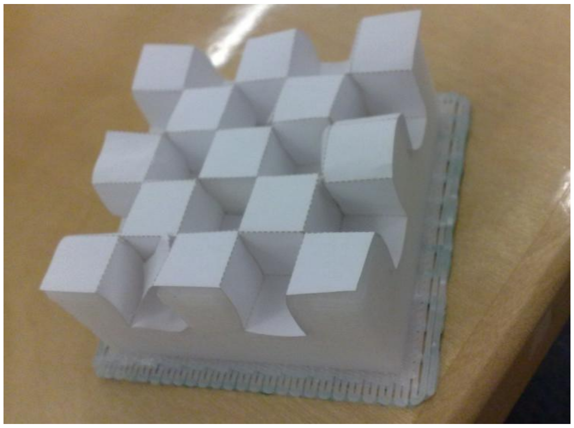


Figure 1.1: Paper pattern on bottom part of mold

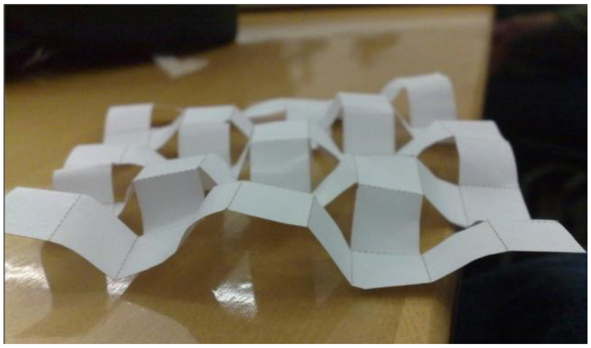


Figure 1.2: Pattern when removed from mold does not hold shape

The results reveal that the folded pattern tends to not hold the shape once removed from the mold, similar to how a folded shape by hand might look. It would most likely be better if a thicker paper stock was used to hold the shape, though the final product may still be too weak to be used for any application.

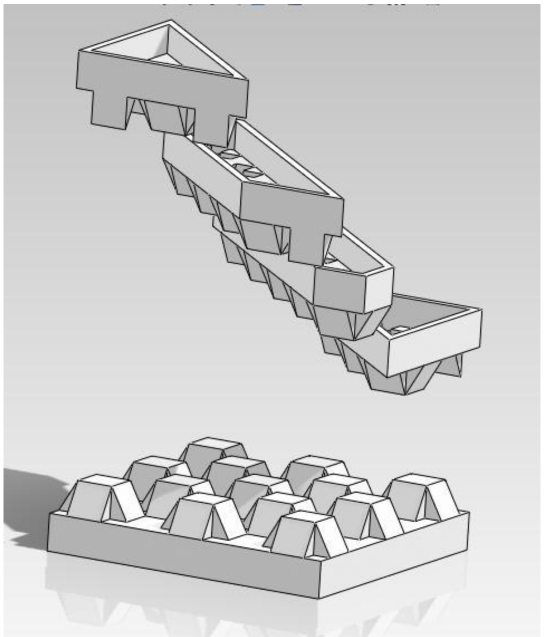


Figure 1.3: 3D model of bottom half of mold and 4-part top molds

Figure 1.4: Multipart molds with different draft angles

It was discovered that a multipart mold was essential if molding was to be used to create a pattern (Figure 1.3, 1.4) which would increase the design work and construction cost.

1.2 Hydro-Fold (Self-Folding Inkjet Printed Paper)

The Hydro-fold method is a fascinating technique of folding which was created by Christophe Guberan, a student at ECAL (Ecole Cantonale d’art de Lausanne, Switzerland). A modified inkjet printer uses a special liquid as the mixture of ink and water. A pre-determined pattern is then printed on the paper and, while the extra moist mixture begins to dry, the paper folds and retracts around the printed and humid lines by using the papers' shrinkability. While lines become edges and the dry surface of the paper becomes volumes, the 2D paper transforms into a 3D structure.

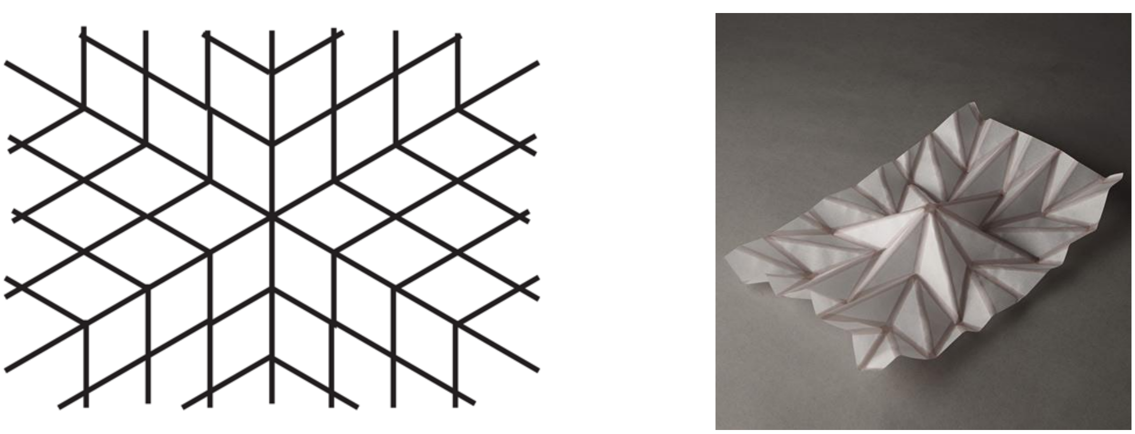


Figure 1.5: Two different folded patterns are illustrated using the Hydro-fold technique

This method seems to be quite successful in creating a technique to fold paper. The final product is aesthetic, lightweight and ‘green’, although it seems that this folding technique does not increase the final product strength.

1.3 Shrinking Thread

The polyester thread sews like normal sewing thread but, when heat or steam is applied, the shrinking thread shrinks about 30%. The paper is pre-cut and pre-creased, based on the origami pattern, and then a thread is sown around the folding line. When the polyester threads are exposed to heat, the thread shrinks and folds the paper around the folding line. Figure 1.6 shows a sample of paper folding using shrinking thread:

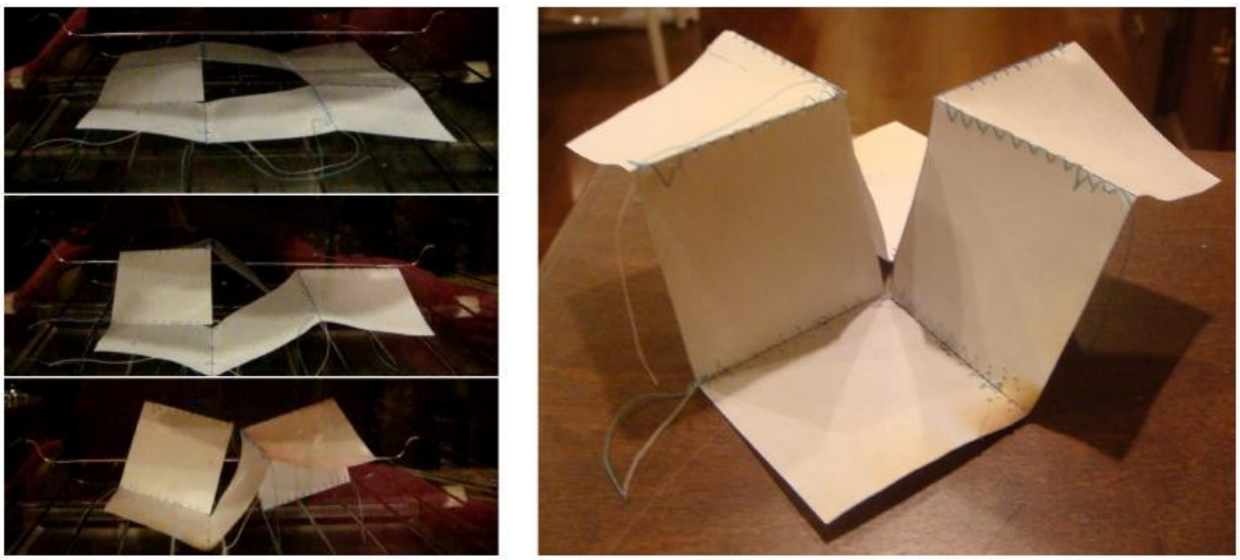


Figure 1.6: Folding paper using shrinking threads

It was found, however, that shrinking thread was quite labor intensive while the results were not precise and controllable enough unless an advanced sewing machine, CNC (Computer Numerical Control), was created made. The idea of using shrinking threads led the research team to utilize yet a different method that utilized thermoplastic polymers for paper-folding in order to find a lower cost and reliable solution for creating folded paper patterns.

1.4 Shrinking Thermoplastic Sheets

Researchers from North Carolina State University attempted to focus on the light-induced self-folding of a pre-strained polymer sheet. A temperature sensitive thermoplastic polymer sheet called *Shrinky Dink®* has been used. Some lines of uneven thicknesses are printed, with a conventional inkjet printer, on the plastic sheets at the spots where the plastic should fold. It is then exposed to infrared light and the printed ink absorbs the light energy which causes the absorption of heat and the shrinking of the polymer underneath the ink. The bold black lines absorb more energy and shrinks faster than the other areas on the plastic, additionally, the bottom of the sheet does not shrink considerably and it causes the plastic to fold around the printed lines.

The different folding angles can be determined by designers to fold the individual hinges.

The systematic control of power, intensity and the light pattern, plus the thickness of the black lines can all contribute to the rate of folding and the folding angle. Moreover, double-sided printing enables users to create more complex structures.

Figure 1.7: 3D structures created by self-folding of *Shrinky Dink®* patterned with a desktop printer.

As shown in Figure 1.7, 3D objects such as pyramids, cubes and zig-zags can be made which are folded around 2mm black bands exposing to light for approximately 15s while the polymer reaches a temperature of about 120 ˚C.

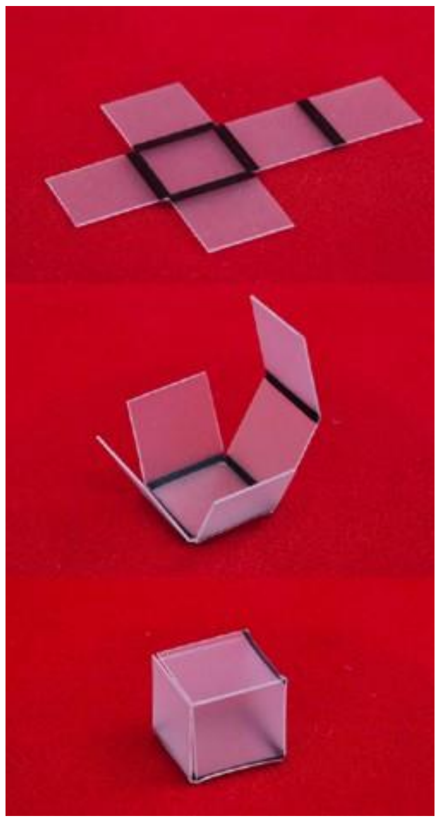


Figure 1.8: Applications such as small boxes used in drug deliveries can be made using this method.

The idea of using shrinking threads and the thermoplastic polymer to make a self-folding process led UBC researchers to come up with a unique idea of developing self-folding paper, which is described in the following section.

1.5 Shrinkage Plastic Method

The aim of this project is to develop a fully automated prototype in order to produce self-folding paper products in large quantities. This project is a direct follow-up to the first project initially explored by Bayless, et al. (Continuous Process for Origami Paper Folding). The original objective of the project was to create a prototype of an automated converter to create complex three dimensional (3D) paper folds based on origami patterns. The first phase of the project began by creating a small prototype capable of cutting small sheets of paper (8.5"x11") and folding them into arbitrary, repeating cellular structure using thermoplastic polymers. The automated prototype was supposed to be portable and operable by a single individual. The next phase was to develop a fully automated prototype to create large-scale self-folding paper products.

This process attempts to fold paper by taking advantage of the phenomenon where certain stretched plastics shrink when heated. The paper is first weakened along the crease line by scoring or by being mechanically pre-creased. A piece of shrink film is affixed on either side of the crease using super glue (cyanoacrylate adhesives). When heat is applied, the film shrinks, pulling in the paper and creating the fold. Applying this to many creases on a piece of paper creates complex folded structures. The angle of the fold can be adjusted by changing the length of plastic across the crease, by using film with different shrink ratios and by adjusting the temperature and duration of the heating. The experiment started using window insulation shrink film (low density polyethylene) which shrinks isometrically so that it does not need to be aligned. Figure 1.9 illustrates how the shrink film can fold a piece of paper.

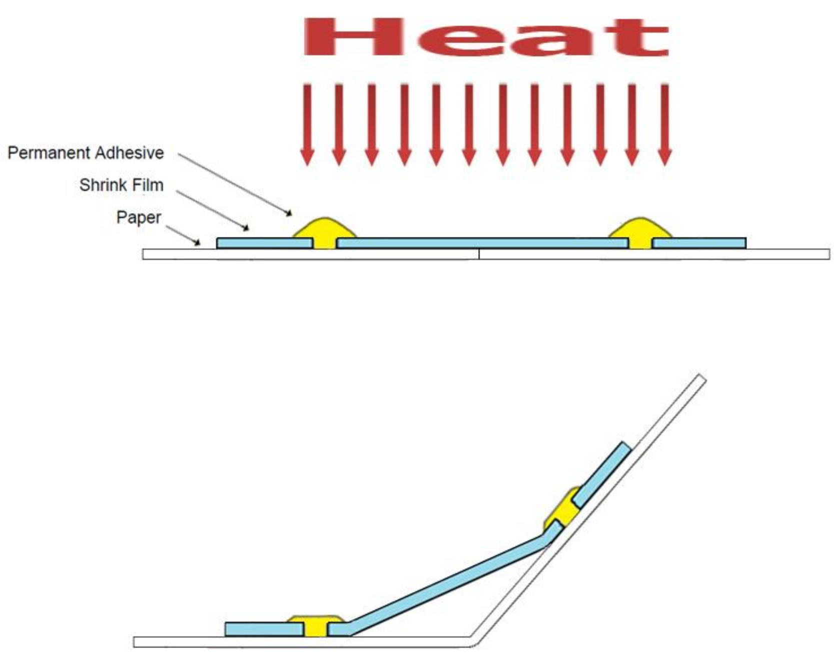


Figure 1.9: Illustration of folding paper using thermoplastic

This technique enables users to form different paper structures which consist of many simple folds by the addition of heat.

1.5.1 Cutting and Creasing

Physical Cutter/Creaser

As a semi-permanent solution for cutting and creasing, a machine was acquired. The machine used for creasing, perforating and cutting the paper, and cutting the shrinking plastic was the Graphtec Craft ROBO Pro (CE5000-40-CRP) cutting plotter (Figure 1.10). The Craft ROBO Pro cutting plotter employs a digital servo drive system to achieve high-speed, high-precision cutting.

In addition to cutting marking film and other media, a CE5000 Series cutting plotter was also used as a pen plotter. This machine is a CNC cutter/plotter capable of cutting everything from thin film to vinyl. This machine was used as a rapid means of accurately cutting and creasing paper patterns as well as cutting the shrinking plastic. It came with necessary accessories such as carrier sheet (adhesive sheet to keep paper stationary), a cutting blade and a pen.

Figure 1.10: The CraftROBO CE5000-40CRP

This machine has multiple settings and conditions that can be set. Any of the conditions can be set for different cutting, perforating and creasing conditions. The papers and polymers with varying thickness need to be creased and cut with different depths. The cutting blade can adjust the force to change the cutting depth.

Computer Aided Drafting (CAD)

All the patterns are created using AutoCAD 2007 software and generated in graphic files, specifically a .dxf file. The advantage of using AutoCAD is having geometrically accurate drawings and the ability to create symmetrical structures with specific dimensions. Any patterns consisting of different cutting and creasing objects, and all the patterns, should be drawn in different layers of cutting and creasing objects, for paper and plastic, in order to be readable for the CraftROBO CE5000.

Software and Programs

Two programs are essential to running the CE5000-40CRP: Cutting Master 2 and a vector drawing program: CorelDraw or Adobe Illustrator, to import AutoCAD drawings (.dxf files). A standalone plotter program called Graphtec Studio can be installed as well. After the installation of Cutting Master 2 and integrating the plugin, settings from the plotting must be specified for different operations (creasing, cutting).

1.5.2 3D Model Designing

There are plenty of available origami patterns (Figure 1.11). Although many of the origami designs are simply decorative designs, origami folds have a greater potential for producing strong structures which can be used for various industrial applications (Figure 1.12).

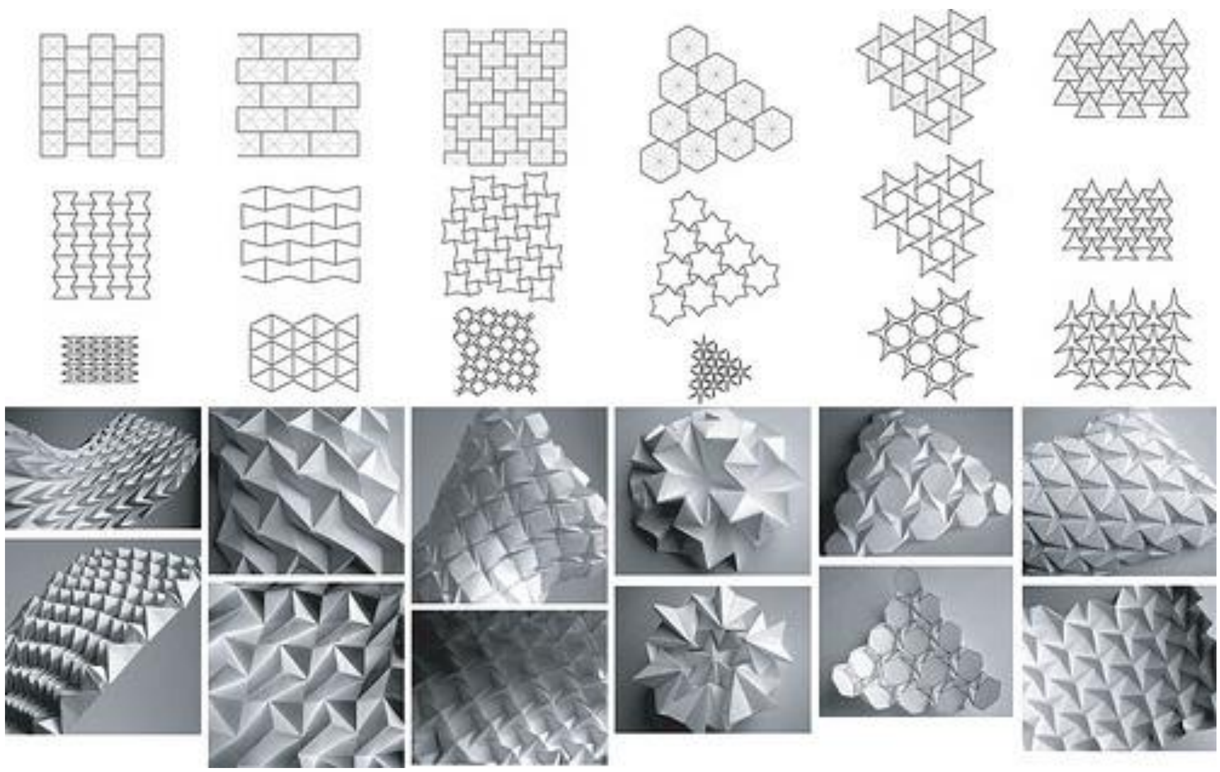


Figure 1.11: Various deployable, transformable structures designed by Daniel Parker

Three dimensional (3D) structures could have many potential applications in different fields. Many available designs have been used or modified for this research. Meanwhile, several new designs have been made to examine the plastic shrinkage method.

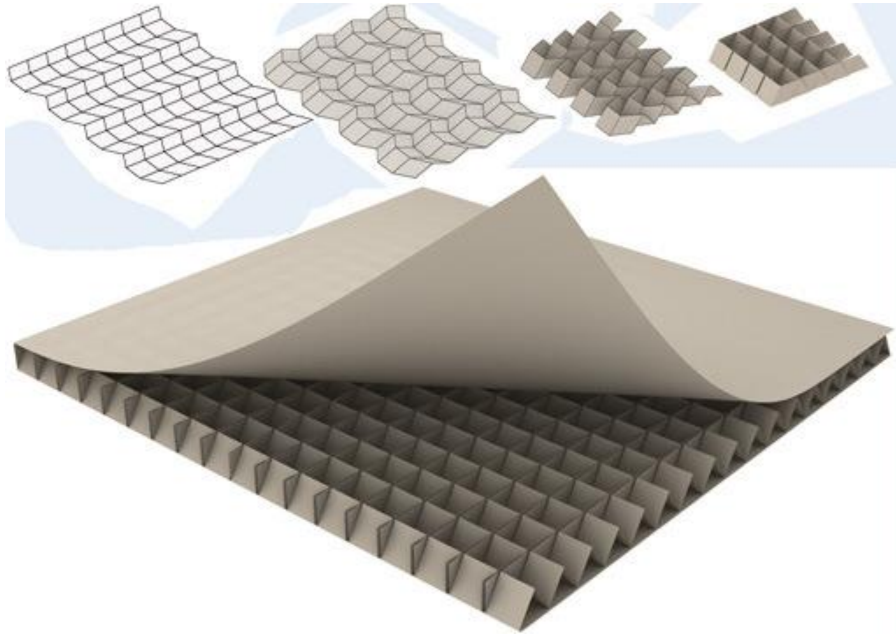


Figure 1.12: An example of an industrial application of the Origami pattern (the paper honeycomb)

The chosen origami pattern is first made and folded by hand to define the direction of each folding line and to determine the plastic position around the folding line. Then, the pattern is drawn in AutoCAD which is optimum for creating CAD models for the creases and cuts due to its ability to superposition multiple layers over each other. The cutting line, creasing or scoring line, and the polymer piece are drawn in separate layers in order to be readable for the cutter software.

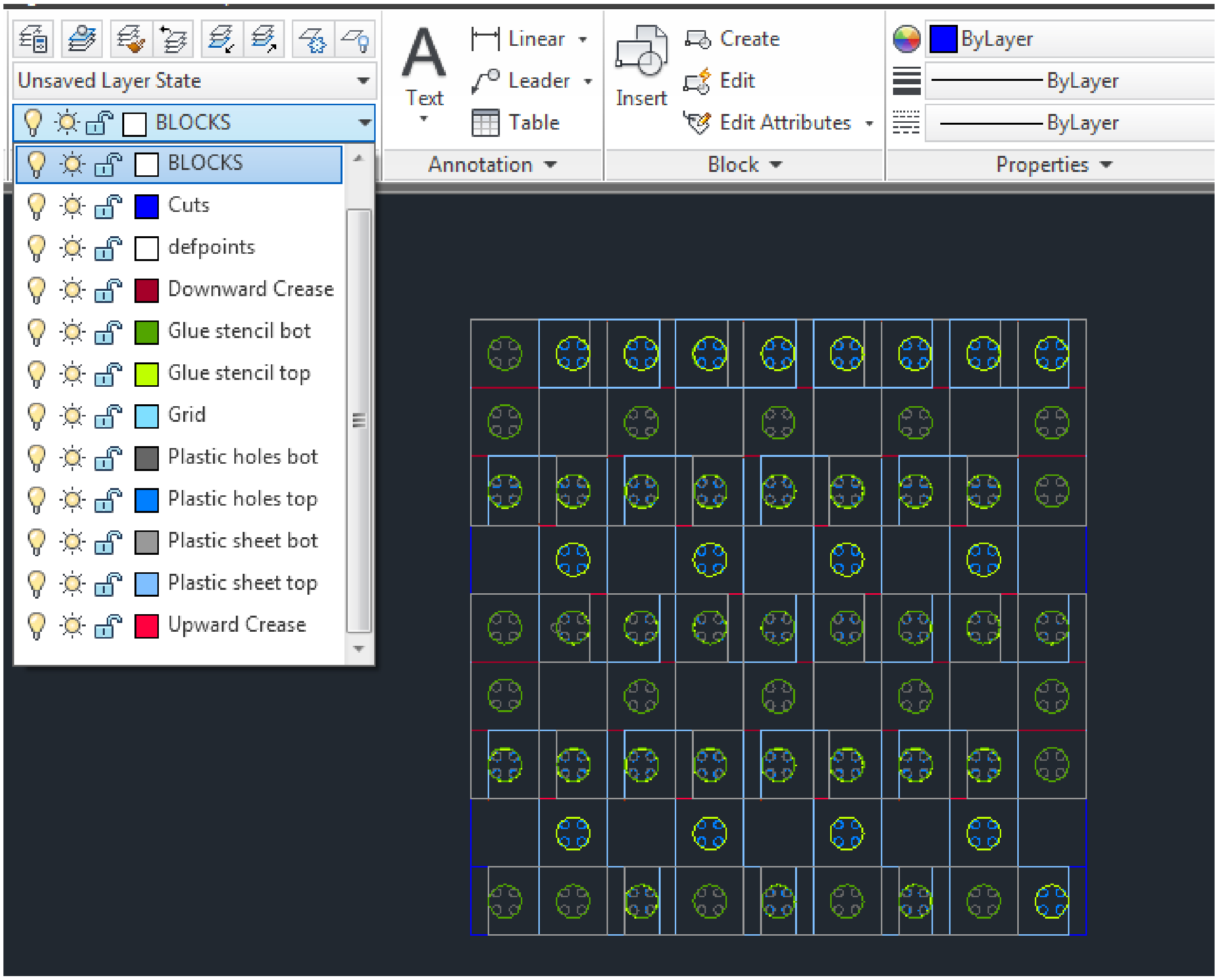


Figure 1.13: A sample AutoCAD cut/crease/shrink pattern with layer names displayed (drawn by Jose Luis Lopez, Julian Fong, and James Simard)

3D Origami Simulator

Certain software is available on the market that is used to simulate how a two dimensional (2D) origami pattern could be folded into a three dimensional (3D) model, while software such as Solidworks and AutoCAD are not able to simulate folding. One of the brilliant software programs designed by Tomohiro Tachi is called the "Rigid Origami Simulator". This design software allows users to interact with origami forms while altering the crease pattern of the model. The software can keep developability (foldable from a piece of paper) and flat-foldability (foldable into a flat shape) (Figure 1.14).

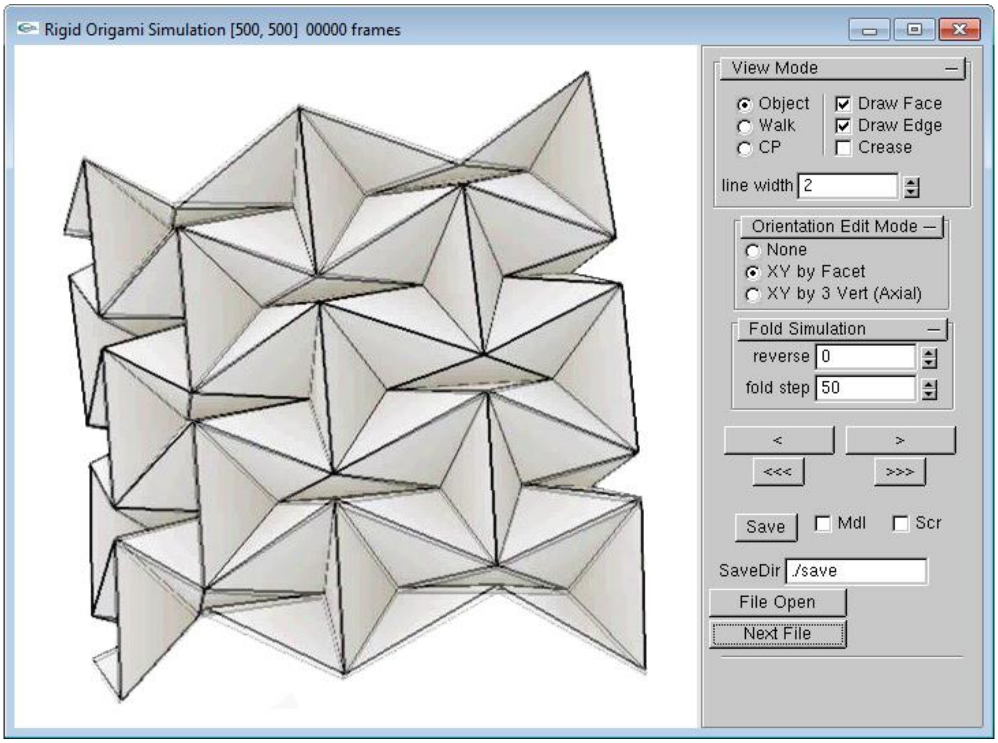


Figure 1.14: Folding simulation with Rigid Origami Simulator software

1.5.3 Attaching Plastic to Paper

The most critical part of making self-folding paper is the process of attaching the shrink film to the paper. Several different materials have been used to attempt adhering plastic to paper. A spray adhesive, 3M super 77 glue, was applied onto the paper via a stencil by a group of Physics students at UBC (Jose Luis Lopez, Julian Fong, and James Simard). The plastic stuck well, but when it was exposed to high temperatures it did not remain attached while it was shrinking.

Other mechanical fastening methods have also been tested such as staples and rivets. Initially, stapling worked well to connect the plastic to the paper but the result was not desirable due to the large weight of the composite, plus it was not aesthetically pleasing.

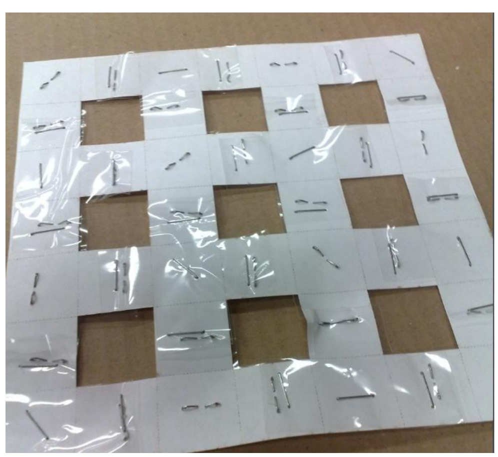


Figure 1.15: Unfolded origami pattern using staples to attach shrinking plastic to paper

To solve the problem of adhering plastic to paper, epoxy rivets were used in a way where 1/16” holes were cut into the plastic and epoxy was applied over the hole onto the paper (Figure 1.16). The overhanging epoxy, and the epoxy that connected the neighboring holes, created rivets that secured the plastic even as it shrunk.

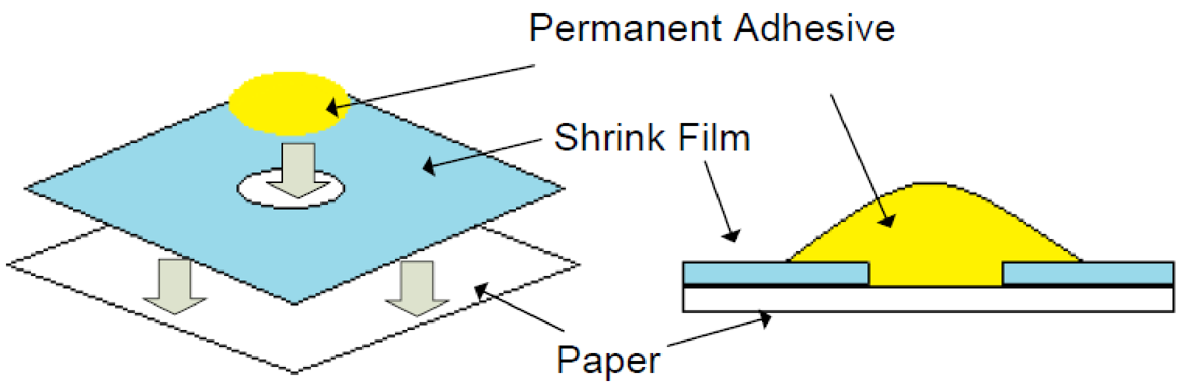


Figure 1.16: Placement diagram of glue rivets with a single hole

Since the plastic is a multidirectional shrink film, various shapes of shrinkage materials can be used for assorted patterns, though it was difficult and a time consuming process to manually attach all the shrink films, piece by piece.

Figure 1.17: Examples of shapes of shrinkage materials used

In order to design the placement of the shrink material, cuts and directions of the creases were determined first. Plastic strips were then placed between the creases on the inside of the bend.
Because of the square shapes of the plastic pieces, the attachments were placed onto the center of the squares and the strip was made into the full width of the grid (1/2”). Where plastic strips

overlapped onto the same attachment, both of them were combined into a single piece making L-shapes, T-shapes and crosses.

1.5.4 Auto-Folding

Based on Nojima and Saito's paper [16] some patterns were produced using the shrinking plastic method (Figure 1.18). A hair dryer or a heat gun can be used to heat the paper-plastic composite uniformly and transform it into a 3D paper structure.

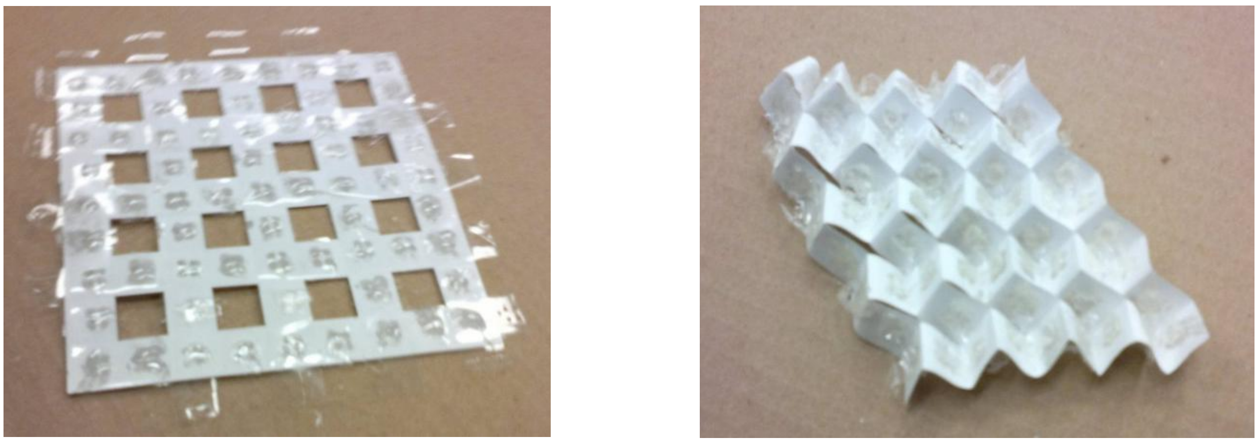


Figure 1.18: Unfolded and folded origami pattern using glue to adhere the shrinking plastic to the paper (made by Jose Luis Lopez, Julian Fong, and James Simard)

1.6 Research Objectives and Thesis Organization

Creating automated self-folding paper remains an area of research that brings many questions regarding the automated folding process in order to make useful and sustainable paper products. Previous literature reviews have introduced several techniques to automate folding but it seems that there is still a lack of success in achieving higher-level goals of making affordable and easy manufacturing process to use paper as an environmentally friendly alternative for a wide range of products, and to produce strong 3D paper structures to replace many harmful polymers and unsustainable plastics products that are currently being used. The objective of this research was to develop a prototype system for automated origami paper folding by using heat as a thermal actuator.

The problems of making an automated prototype are discussed in Chapter 2 and related solutions are offered and applied. In the procedure of automation, a new technique was developed for adhering plastic to paper using a heat-weld device. Some significant factors which affect the strength of paper-polymer adhesives were recognized. Another objective of this research was to identify the effective factors and their impacts on the paper-polymer bond strength. A recent study has been done by conducting a series of experiments. A description of the experimental methods and results is presented in Chapter 3. The next phase of the project included simulating paper folding and studying the significant factors which determine the accurate fold angle to create the desired 3D origami structure. The effects of factors such as temperature, paper thickness and the attachment distance to the fold line are discussed in Chapter 4. The employed technique to create self-folding paper was successful and led us to produce a range of 3D structure paper products as a main objective of this research, and potential applications are illustrated in Chapter 5, followed with recommendations for future work.

Chapter 2 – Prototyping Automated Origami Paper Folding

The main idea of the self-folding paper technique using shrinkage plastic is described in section 1.4, and the process of folding paper with shrink film proved successful after having folded several repeating structures. However, it is still far from being a fully automated self-folding paper prototype. Also, during the course of developing the method to make more complicated products with a better final shape, some problems arose:

2.1 Problems in Automating Paper Folding Shrinkage Method

Some problems are categorized in the Shrinkage method and described in the following sections to outline the problems:

2.1.1 Adhering Plastic to Paper

Gluing plastic to paper can be accomplished with different types of glue. The first problem is that gluing by hand is a time consuming and inaccurate process since all the pieces of plastic need to be adhered one by one. In addition, there are other disadvantages to using glue as an adhering material which are described below:

-According to the many trials and errors, a thin layer of glue is not strong enough after being exposed to heat and drying. When the composite of paper and plastic is heated using a heat gun or being placed in an oven, all the connections would dry and lose their adhering properties.

-Increasing the weight of the product:
One of the advantages of making a paper structure is to have a lightweight product. Using glue as a medium to attach plastic to paper, in addition to making a less green product, will make a heavier final product.

-Aesthetics:
To make a neat and artistic product, it is essential to reduce the amount of glue or remove the glue all together, as the adhering medium.

2.1.2 Shrinkage Material

A very thin window of insulation shrink film (low density polyethylene) has been used to fold paper when it contracts. This polymer can apply a low amount of force on the paper while it shrinks and is just enough to be able to fold a thin paper stock. Though this plastic shrinks in low temperature and in a shorter time due to its thinness, to fold thicker paper and cardboard there is a need for a higher amount of force. On the other hand, even if the shrinkage polymer can apply higher force, the attachment strength should have the same or higher strength than the applied force to properly transfer the force without disconnecting.

2.1.3 Automation

There are three main parts in making a product by utilizing this method. Firstly, by the cutting and creasing/scoring of paper and plastic, secondly, by aligning the pieces of plastic on paper and thirdly, by affixing and adhering plastic onto paper using glue.

2.1.3.1 Cutting, Creasing and Scoring:

A Graphtec CraftROBO (CE5000-40-CRP) is a proper device to cut and crease paper and plastic with almost any details based on the patterns designed using computer software. This step is a semi-automated part of the procedure but there are two limitations in using it. First, it cannot cut/crease any media larger than the A3 size and second, the sticky carrier sheet and cutting media is bent during the cutting/creasing procedure which means that it is not possible to cut thick and rigid media with low flexibility.

2.1.3.2 Aligning Plastic Pieces on Paper:

After cutting paper and plastic, the plastic pieces should be placed on the preset positions on the paper. To automate the entire process, a mechanism should be designed to place all the plastic pieces at the same time and in the correct positions.

2.1.3.3 Bonding Plastic and Paper:

This is the last part of the process that needs to be automated. This can be achieved by various means including mechanical, robotic, electrical, or a combination of them all. The main benefit of automation is to improve quality, accuracy and precision. An autonomous solution to attach the plastic to the paper could be obtained by designing and building a device that, instead of using glue as the adhesive, perhaps utilizes a robotic device, such as a robotic arm, to satisfy two of our system requirements:

-Finding the exact points needed to add or connect the adhesive material.
-Adding the required amount of adhesive.

2.2 Solution to Automating Paper Folding Shrinkage Method

Pertinent information is provided in the following sections to outline the problem regarding the automated self-folding paper process using shrinkage plastic. Three main problems are discussed to obtain the best result. The solutions for all the problems are discussed and some solutions are provided in the following section:

2.2.1 Shrinkage Polymers

A low density polyethylene, initially used in the first step of the design, is a very thin plastic with a high sensitivity to heat and it was basically a temporary material used to examine the plastic shrinkage method. However, further experiments revealed the need to use different polymers with different characteristics. To fulfill the needs of the plastic shrinkage method, the use of thermoplastics is required.

A thermoplastic is a polymer which becomes moldable above a specific temperature and returns to a solid state after cooling. Most thermoplastics have a high molecular weight. The polymolecule chains associate through intermolecular forces which permit thermoplastics to be remolded since the intermolecular interactions increase upon cooling and restore the bulk properties. There are several different thermoplastics:

1- Acrylic
2- Nylon
3- Polybenzimidazole
4- Polyethylene
5- Polypropylene
6- Polystyrene
7- Polyvinyl chloride
8- Teflon

There are two significant polymer properties which affect the results such as the folding angle, folding sequency, and the method of adhering polymer to paper in the plastic shrinkage method:

2.2.1.1 Polymer Shrinking Temperature

There is a particular temperature for any thermoplastic where the polymer starts being soft and moldable; that temperature is called the glass transition temperature (T_g). Above the glass transition temperature, and below its melting point, the physical properties of a thermoplastic changes drastically without any associated phase changes. Utilizing thermoplastic with different glass transition temperatures in a product enables us to have a sequence of folding while the temperature is rising in order to make complicated models. Also, the sequence of folding can be provided by using the same thermoplastic with different thicknesses (the thicker polymers take more time to shrink).

2.2.1.2 Polymer Shrinkage Ratio

There are two main types of polymers: thermoplastics and thermoset plastics. The main difference between them is that thermoplastics can be made malleable at high temperatures. Thermoplastics can be molded between 65 ~ 200 ºC in a number of ways. They differ from thermoset plastics in that they can be returned to their plastic state by reheating and they are also recyclable. Methods of shaping the softened plastic include: injection molding, rotational molding, extrusion, vacuum forming, and compression molding. The molding process of thermoplastics determines the amount of the polymer shrinkage ratio. However, precise evaluation of the shrinkage ratio during the heating process is difficult because it is related to various factors.

Among all the mentioned thermoplastics, polystyrene is one of the most widely used plastics which are produced in large amounts of several million kilograms per year. It is also a very cheap resin that is typically transparent, hard and friable and it has a relatively low melting point. Polystyrene can be produced in a transparent or frosted form.

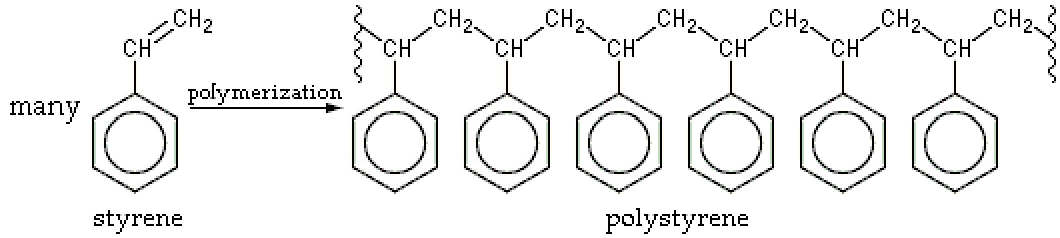


Figure 2.1: Polystyrene formation

In chemical terms, polystyrene is a long chain hydrocarbon wherein alternating carbon centers are attached to phenyl groups. Polystyrene's chemical formula contains the chemical elements carbon and hydrogen. Since the molecules are long hydrocarbon chains, consisting of thousands of atoms, the total attractive force between the molecules is exceptionally large. When heated, the chains are able to take on a higher degree of conformation and slide past each other.

This intermolecular weakness confers flexibility and elasticity. The ability of the system to be readily deformed above its glass transition temperature allows polystyrene (and thermoplastic polymers in general) to be readily softened and molded upon heating.

Shrinky Dinks® is a children's toy onto which one can draw a picture and subsequently shrink it to a small fraction of its original size. It consists of thin, flexible sheets of polystyrene. *Shrinky Dinks*® contract in the oven in temperatures ranging between 325 ^{o}F and 350 ^{o}F, to approximately 33% of their original size, and becomes nine times thicker. The shrinkage properties of this product are due to manufacturing process and depend on how much it is drawn and stretched while polystyrene is formed into thin sheets, and it is also a function of temperature, method, and speed of processing.

Figure 2.2: *Shrinky Dinks*® sheets

2.2.2 Attaching Polymer to Paper

Using glue as an adhesive media is problematic and mainly related to the strength of the attachment, the weight of the product and aesthetic appearance. The idea of not using any media as an adhesive is based on the main property of polystyrene as a thermoplastic polymer that is the malleability of polystyrene when it is heated between T_g and T_m. As the temperature of the polystyrene rises beyond its glass transition temperature, polymolecule chains move easily over each other and the polymer enters a flowing state which allows it to work into the fibers of the paper through the applied pressure. When the heat is removed and the polystyrene cools, it solidifies again, attaching itself to the paper.

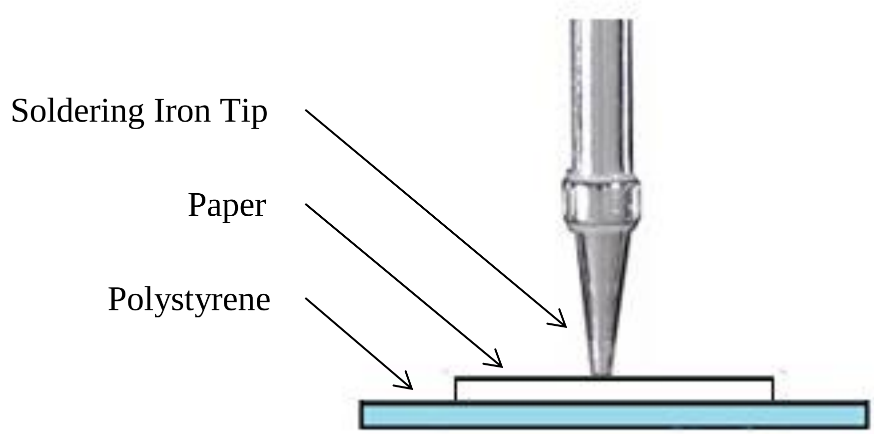


Figure 2.3: Positioning of the soldering iron, paper, and polystyrene for attachment. The iron pushes down on the paper to weld the polystyrene to the paper.

Polystyrene is attached to the paper using concentrated heat and pressure which is applied with a soldering iron from the paper side. The setup can be seen in Figure 2.3. The heat and pressure causes the polystyrene to enter a glass state which then flows into the paper. When the iron is removed, the partially liquid polystyrene solidifies and effectively welds to the paper. If the polystyrene is attached across a fold line (crease line), and is then heated until it shrinks, it can induce folding in the paper. The heat weld method has proven to be successful in attaching polymer to papers without any coating. After further examination, it was determined that significant variables alter the outcome of the experiment. Listed below are those variables:

1- The thickness and type of paper.
2- The temperature of the soldering iron tip.
3- The sectional area of the soldering iron tip.
4- The amount of pressure applied on the compound by the soldering iron.
5- The amount of time pressure is applied.

Adjusting any of the aforementioned factors would affect the bond strength, and by changing the different bond strengths it can be made into different types of paper and cardboard with varying thicknesses. Since studies to scientifically measure the impact of the aforementioned variables on the paper-plastic bond strength using heat weld have been seldomly performed, an experiment was conducted; it is explained and discussed in chapter 4.

2.2.3 Automation

As discussed, there are three main parts that are needed to get automated status: cutting, creasing and scoring, aligning plastic pieces on paper, bonding plastic and paper.

2.2.3.1 Cutting, Creasing and Scoring Automation

The first step is to automate the folding process which was fulfilled by purchasing an advanced large format flatbed cutter/plotter “Graphtec FC2250 Cutter/Plotter”. The table size is 68.5″x36″.

Figure 2.4: Graphtec FC2250-180

Graphtec FC2250 has a higher accuracy in cutting as opposed to the Graphtec Craft ROBO Pro (CE5000-40-CRP). Furthermore, it has the ability of cutting and creasing paper and polymer sheets in thicker and larger sizes.

This machine is also featured with a dual head design which enables users to cut materials with two different forces: 500 grams and 1000 grams. The electrostatic surface holds paper on the table instead of using a sticky career sheet in the CE5000-40-CRP.

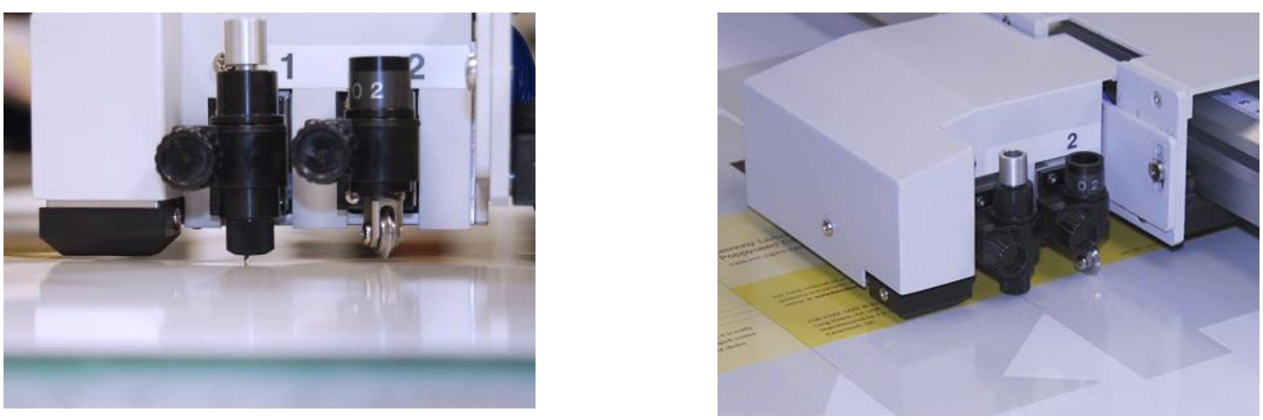


Figure 2.5: Graphtec FC2250-180 dual head design: 500/1000 grams cutting force

2.2.3.2 Bonding Plastic and Paper Automation

The second step in the autonomous paper origami procedure is to create an automated system to attach plastic material to the paper at desired points by using heat and pressure. A few design paths were considered to solve this problem including designing a printer-like device and a robotic arm. Both options are explained in Appendix J but using the servo-robot was an unsuccessful attempt to automate the attaching polymer to paper process. An alternate idea was to use the FC2250-180 accuracy to perform this task. The thought here was to replace one of the blade holders with a new part to hold the soldering iron. The steps required to set it up were to add the modified piece to hold the soldering iron, set the machine settings, add protective sheets in the cutting area to prevent damage to the cutter surface in the event of an error, and setting up the soldering iron.

In order for the FC2250 to hold the soldering iron in place, a specialized holder head and jig needed to be designed. To avoid transferring heat from the soldering iron to the other part of the cutting machine, a high heat resistance plastic was used to hold the soldering iron. Extreme-Temperature Slippery PTFE, which can withstand highs of 500° F and lows of -330° F, was used to make the holder of the soldering iron. The new part was designed and drawn in AutoCAD based on soldering iron dimensions.

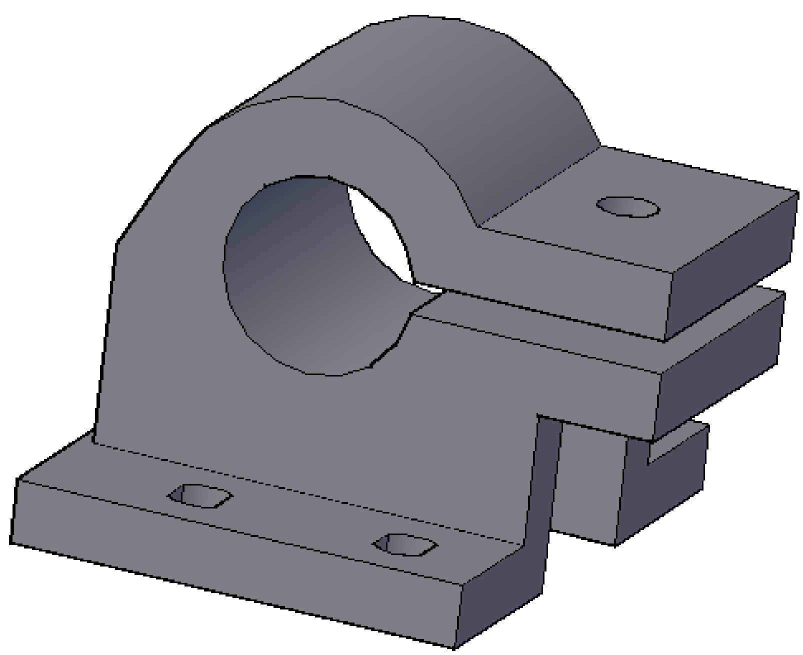


Figure 2.10: Soldering Iron Holder 3D model

Installing the soldering iron on the Graphtec FC2250 enables the user to combine cutting, creasing, perforating, painting paper and plastic in addition to attaching pieces of polymers onto the paper. Replacing one of the blades with a soldering iron was a successful attempt to automate the attaching polymer accurately, though the amount of pressure that was applied by the soldering iron was a significant factor which determined the paper-polymer bond strength. Different types of paper with different thicknesses needed a certain force to have the strongest paper-polymer bond strength. The amount of pressure can be set in the FC2250. There are also some other significant factors that affected the attachment strength. Based on the many practical experiments, the amount of pressure applied onto any of the attachment differs from model to model. This means, in addition to the aforementioned significant factors, any model requires a certain amount of paper-polymer bond strength. To measure the effect of all variables, an experiment has been conducted to measure the bond strength. The experiment and its result is explained and discussed in the next chapter.

2.3 Conclusion

A thermoplastic polymer was used effectively to fold the paper and form it into various paper structures. The whole automated procedure is summarized and listed below:

1-Computer-Aided Design and Folding Simulation

A three dimensional model is chosen or created and then the unfolded 2 dimensional pattern is drawn in AutoCAD. Afterwards, folding is simulated in the Rigid Origami software to locate the correct size of polymer to add in addition to the proper places on the paper to adhere the pieces of polymer to.

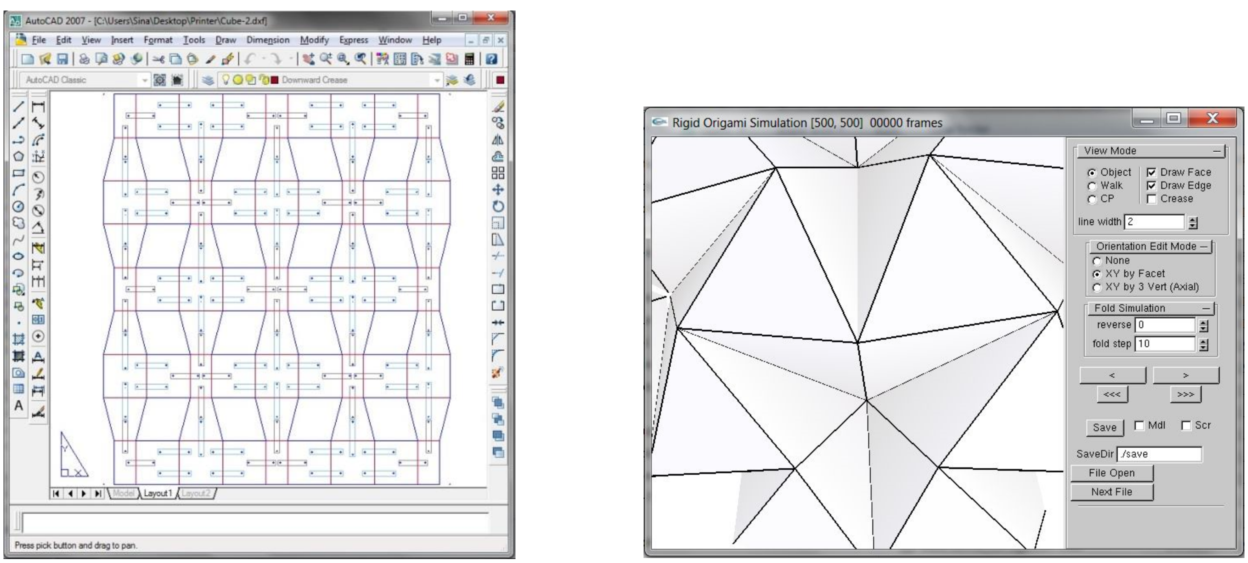


Figure 2.11: CAD design and folding simulation example

2-Cutting/Creasing/Polymer Welding:

The polymer sheet is located on the large flatbed cutter and is then cut based on the design. The paper sheet is then located on the polymer sheet where the cutter would begin to crease and cut the paper. In the last step, the cutter, which is modified to carry a soldering iron, would weld small pieces of polymer to the paper. The unused portion of the polymer sheet can then be removed easily and the welded polymer strings would remain attached onto the paper.

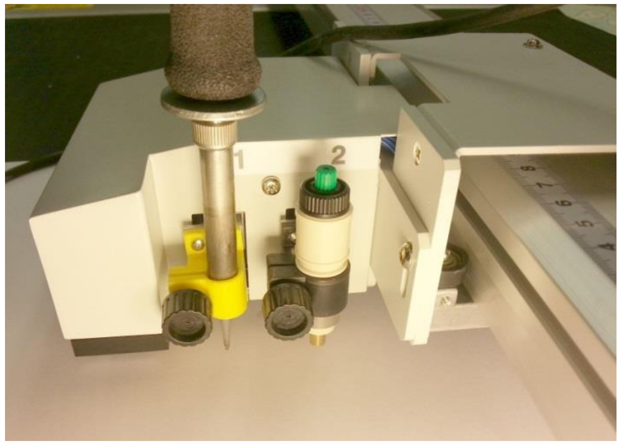


Figure 2.12: Cutting paper, polymer sheet and adhering polymer to the paper all done automatically in one step.

If the final product is heated to the particular temperature of 100°C, the polymer starts shrinking and the paper begins to fold and transform into a 3D structure. With the exception of placing plastic pieces on paper the whole process is automated and the development of this prototype enables us to make self-folding paper automatically.

Chapter 3 - Paper-Polystyrene Bond Strength in Heat Weld Method

3.1 Objective

An automated prototype to create self-folding paper has been made successfully. To optimize the procedure for attaching plastic to paper, we need to carry out a measurement study regarding the quality of paper-polymer bond strength. During research, some significant factors that impacted the quality of the attachment had been recognized. Such examples include temperature, pressure, the soldering iron tip sectional area, paper thickness and time. The objective of this study is to reveal the significant factors, their effective range, their impact on the paper-polymer bond strength and a database of strength attachments with an effective factors variation.

3.2 Experimental Method to Measure the Bond Strength

In order to measure the paper-polymer bond strength using the heat weld method, we need a controllable device to hold a soldering iron (Figure 3.1) while its temperature is able to be adjusted, and while it is being pushed into the paper side of the paper-polymer composite (Figure 3.4) with a certain force. The applied force is measured using a digital scale (Figure 3.3) while the force is applied on the composite over the digital scale. Then, the strength of the attached paper and polymer is measured by the electronic tensile tester (Figure 3.2). Two different methods were used to hold and control the soldering iron to heat weld the paper to the polymer which is described in next section.

Figure 3.1: The temperature controlled soldering iron, Model “Weller WES51”

Figure 3.2: The electronic tensile tester, Model QC II

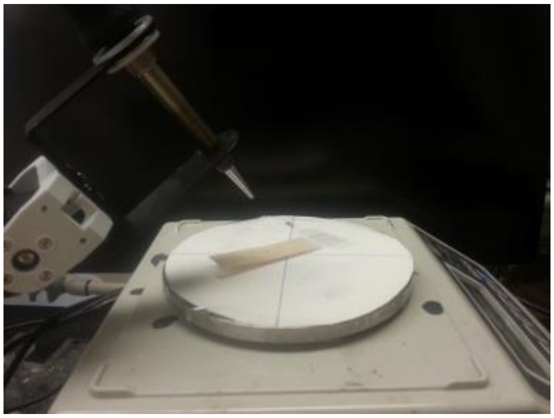


Figure 3.3: Digital scale to measure the applying pressure

Figure 3.4: Paper-Polymer test sample

3.2.1 Strength Attachment Measurement Using the Servo Robot

The servo robot was utilized to run the test first. The temperature was controlled by using the soldering iron controller and the time and strength was controlled by the delay and angle parameters of the arm. By increasing or decreasing the angle of the wrist joint, the arm would apply more or less pressure within a range. The Arduino code is available in Appendix H.

The method that is developed to measure the bond strength is to, firstly, put a rectangular piece of paper and polymer together at a size of 15mmx50mm (Figure 3.4) and then place it over a digital scale. A soldering iron is carried by the servo robot and it applies pressure onto the compound on the paper side (Figure 3.3).

The servo robot is controlled and programmed by Arduino software. The Z-directional tensile strength of the bond is measured by the electronic tensile tester (Figure 3.2).

Based on numerous trials, some significant variables altered the outcome of the experiment. Listed below are those variables:

1- The thickness and the type of paper.
2- The temperature of the soldering iron tip.
3- The sectional area of the soldering iron tip.
4- The amount of pressure applied on the compound by the soldering iron.
5- The time of applying the pressure.

Since the adjusted temperature on the soldering iron station is not the temperature of soldering iron tip, a digital temperature reader is used to measure the temperature for each test.

The amount of pressure can be changed by varying the angle of the robot wrist and to measure the related pressure, a digital scale was used when the pressure was being applied.

An acceptable range of mentioned variables to have an attachment are found as below:

-Temperature:

The optimum temperature range is 90°C-110°C which reveals that the best heat weld attachments usually happens around the Glass Transition Temperature (Tg).

-Pressure:

The minimum force required to make the weakest attachment is approximately 350gf at the highest temperature. The maximum effective force is about 2000gf.

-Soldering Iron Tip Sectional Area

Based on some of the experiments, only very sharp tips can make an attachment.
Using the servo robot to measure the attachment's strength was unsuccessful due to the increase of force onto paper. The robot wrist joint should bend more and at some point, when the wrist joint bends too far, it would move inwards or slide and make the arm unusable. Furthermore, in order to increase the force on the surface, which the paper was located on, it had to be elevated and the soldering iron would touch the surface at a different angle and the connection would change. Since the connection area (soldering iron tip area) is a significant factor, we need to keep it constant.

3.2.2 Strength Attachment Measurement Using a New Experimental Setup

Servo robot circular motion caused a problem with the paper-polymer adhering. To solve this problem we need to replace the circular motion with a linear motion which requires a new experimental setup to apply a certain pressure onto the paper-polymer in a straight line. The linear actuator is a common mechanism used to generate a linear motion. A mechanical linear actuator converts the rotary motion into a linear displacement via screws. The linear actuators are built for a different range of speed and force. The load capacity can be adjusted by changing the input voltage. The linear actuator is normally used to carry the load but in this experiment it was used to apply the force onto a surface and, based on the type of actuator, a small rotational force was needed to exert a large axial force. A tubular high-speed linear actuator of 1 inch stroke size was used to generate a linear motion. The actuator was bought from the Progressive Automation Company. The specifications are shown in chart below:

Input Voltage: 12 VDC	Mounting holes: 0.35" diameter	Made from aluminum allow
Current: 9A at full load	Screw: ACME Screw	IP Grade: IP54
Load Capacity: 11 lbs, 22 lbs and 33 lbs push and pull	Duty Cycle 20%	Low Noise Design: db<45 (A)
Stroke length: 1" to 24"	Operational Temperature: -6ºC~65ºC (-15ºF~150ºF)	Metal Gears High Speed motor

Table 3.1: PA-15-1-11 tubular high-speed linear actuator specification

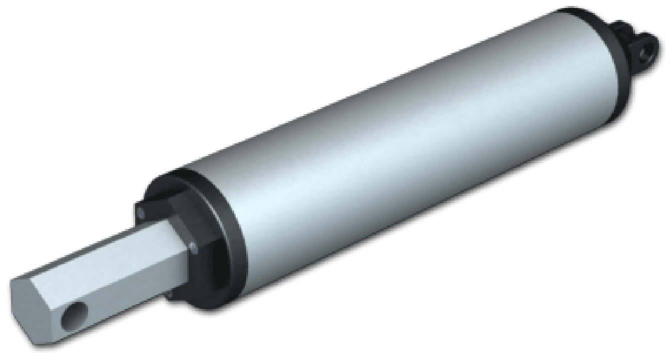


Figure 3.5: PA-15-1-11 tubular high-speed linear actuator

The following criteria should be fulfilled to conduct the experiment:
-A platform should be designed to hold the linear actuator plus a holder to connect the soldering iron to the actuator.
-An electric circuit should be designed to control the motion, speed and power of the actuator.
-The applied force should be controlled to obtain the exact pressure on the paper-polymer composite.
-The force should be applied vertically onto the paper-polymer surface.

3.2.2.1 Experimental Setup

The whole structure was made of aluminum plates which can be assembled by using only bolts and nuts or by being locked into each other. The platform consists of four main parts:

1- A base to keep the platform balance.
2- Two adjustable height stands to hold the actuator. Adjusting the height of the actuator enables us to change the amount of the applied force.
3- A circular guide support to prevent actuator displacement in horizontal directions.
4- A holder to connect the soldering iron to the linear actuator shaft.

All fabrications drawings were made using AutoCAD. All the parts were cut with a water jet cutter in the mechanical engineering department's (UBC) machine shop. The drawings with dimensions are illustrated in Appendix I.

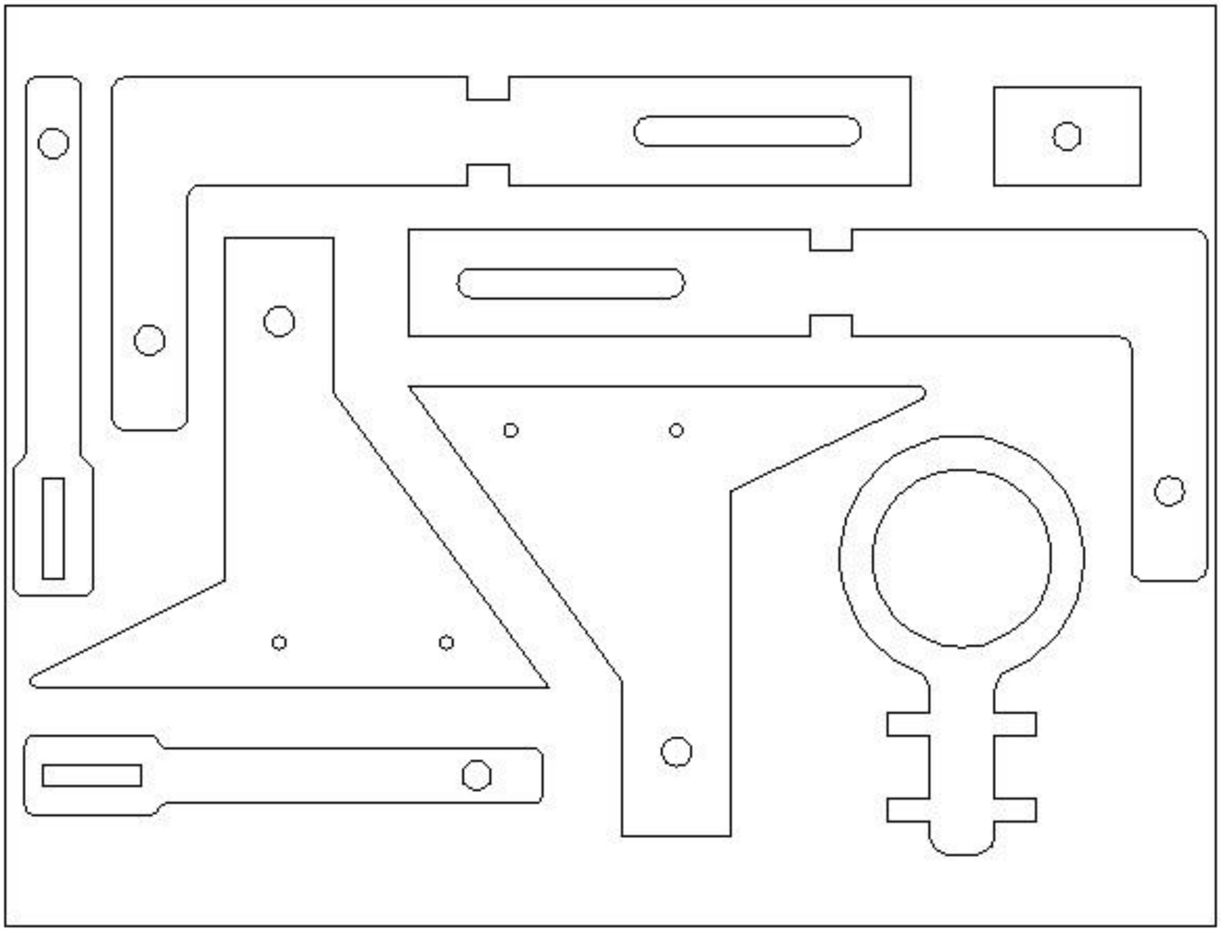
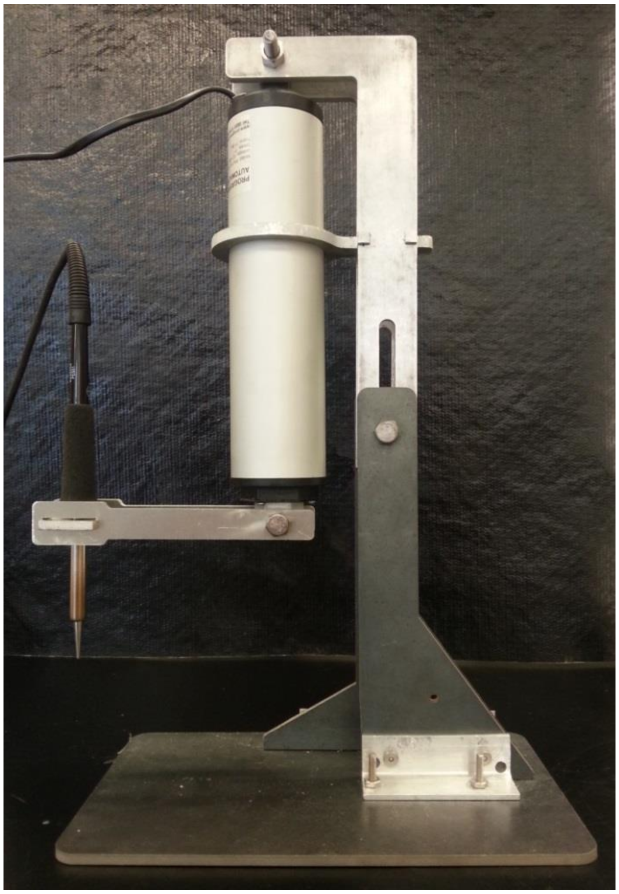


Figure 3.6: Linear actuator platform fabrication drawing to be cut by waterjet cutter. This arrangement was used to save material.

All the pieces were attached to one another as shown in Figure 3.7. Part (1) was bolted to a base plate and the two L-type arms (2) were bolted to the lower stands (1) so that the actuator elevation could be adjusted. The linear actuator was hung from the upper stands (2) using a stud bolt. To avoid actuator displacement in horizontal directions, a clamp (3) was used to guide the actuator. The clamp was matched to the upper arms (2) using four extra parts in part (3) and four holes in part (2) and the force was required for assembly. Two similar arms (5) held part (4) with a hole in it to hold the soldering iron.



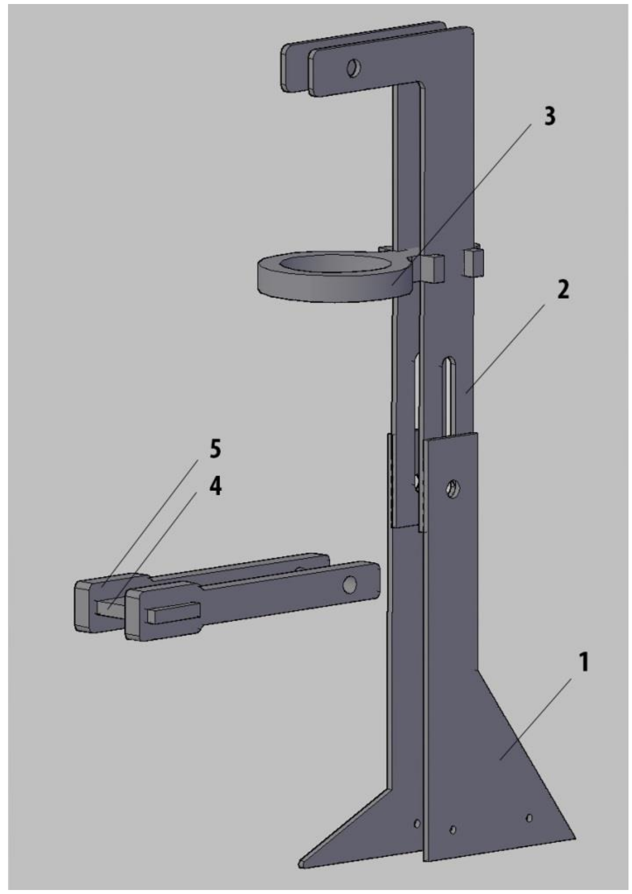


Figure 3.7: The assembled platform and 3D model drawing.

3.2.2.2 Force Control and Calibration

A rocker switch and a speed controller were used to extend and retract the actuator to perform the experiment. The wiring diagram, which is taken from actuator's datasheet, is illustrated in Figure 3.8 and 3.9.

Rocker switch terminal	Connection to
T1	Battery Positive Terminal (+)
T2	Actuator Terminal 1 (Black)
T3	Battery Negative Terminal (-)
T4	Battery Negative Terminal (-)
T5	Actuator Terminal 2 (Red)
T6	Battery Positive Terminal (+)

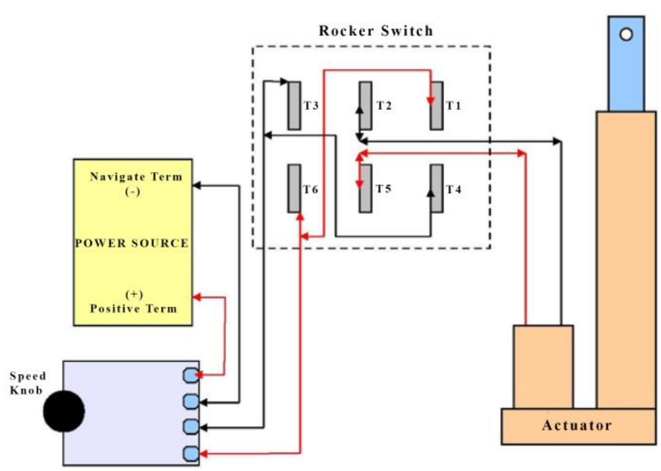


Figure 3.8: Wiring the linear actuator to the rocker switch for double action (extension/retraction) and to the DC speed controller

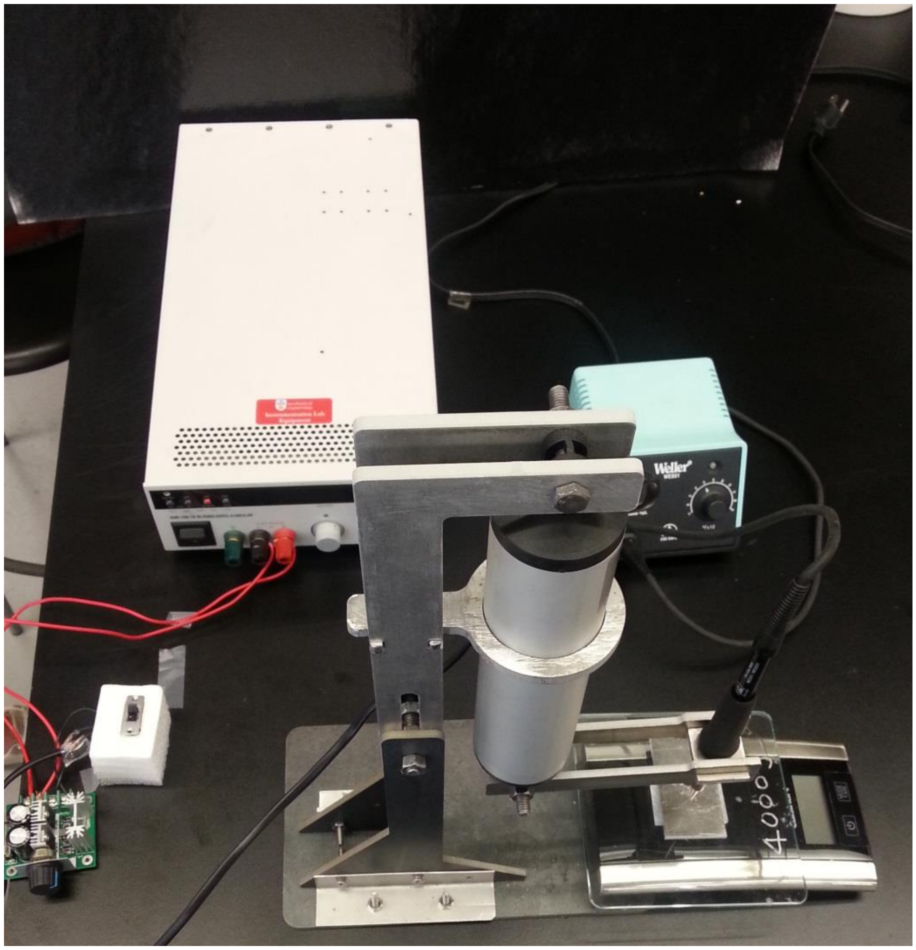


Figure 3.9: Linear actuator wiring

The force range required to run the heat weld experiment is about 500gf and 2000gf. According to the linear actuator's specifications, this load range can be provided by adjusting the electric current between 0(A) and 5(A).

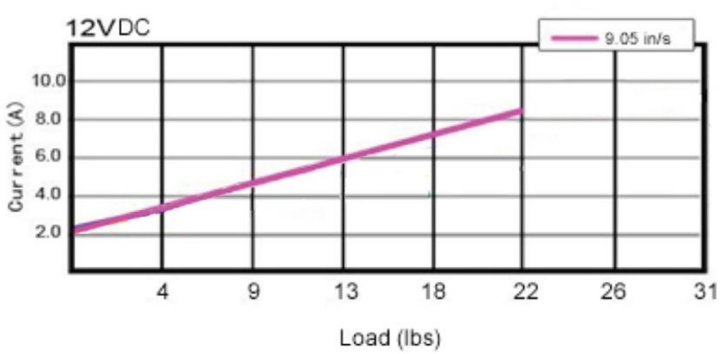


Figure 3.10: Correlation between load and current in the linear actuator model PA-15-1-11

Due to the actuator's mechanical limitations, it is not possible to get that low of an amount of force. As springs are great for absorbing energy, a coil spring was located under the actuator shaft to solve this problem. The spring absorbs the shaft energy and less force is transferred to the soldering iron. To decrease the transferred force, the spring can be stretched more by adding additional layers of thin metal sheets under the spring.

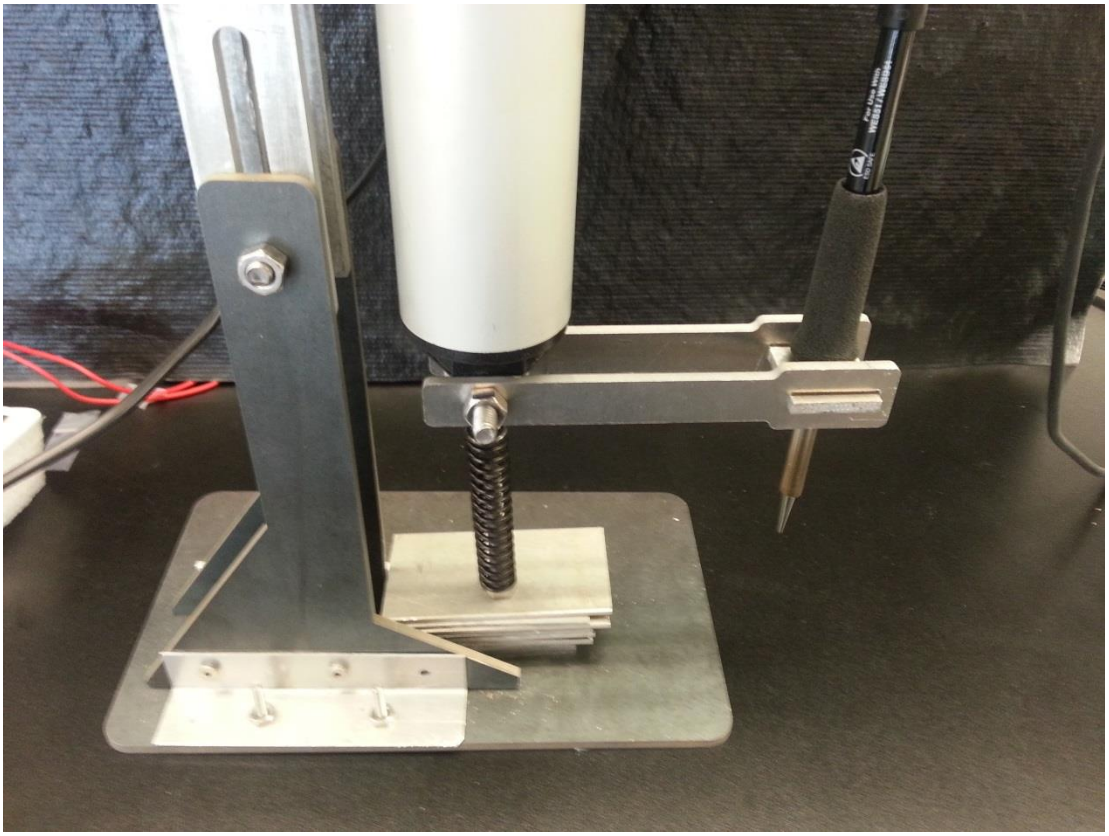


Figure 3.11: A coil spring used to absorb actuator energy and transfer required force onto the paper-polymer sample.

3.2.2.3 Experimental Test

The aim of this experiment is to make a statistical model that can be used to attempt to assess the relationship between effective independent variables such as temperature, force, paper thickness, heat weld contact area on the paper-polymer attachment strength as a dependent variable.

Experiments were performed to measure the attachments strength for a range of dependent variables: heat weld temperature, force, paper thickness and heat weld contact area as summarized in table 3.2.

Temperature (°C)	Force (gf)	Contact Diameter (mm)	Paper Thickness (mm)
90, 100, 110	500, 1000, 1500, 2000	1.2, 1.8, 2.4	0.1, 0.18

Table 3.2: Experimental test plan for temperature, force, contact diameter and paper thickness.

Multivariable analysis allows us to determine the independent contribution of each of these variables to attachment strength. 72 series of experiments for all combinations of independent variables were tested. For each condition, the experiment was repeated for 15 samples of paper-polymer and attachment strength was measured using the electronic tensile tester, Model QC II (Figure 3.2) located in the Pulp and Paper Centre (UBC) laboratory.

3.3 Experimental Result and Discussion

Approximately 15 samples of paper-polymer were tested for each point to obtain a mean value with suitable confidence. All data is summarized in Appendix F and G.

Effect of Temperature and Force

The comparison of bond strength changes for a range of temperature T=90, 100 and 110°C and a range of force F = 500, 100, 1500 and 2000gf with constant paper thickness (t = 0.1 mm) and constant tip diameter (D = 1.2 mm) is shown in Figure 3.10. The error bars represent the 95% confidence intervals. It is evident from the plot that both temperature and force are factors affecting the mean failure force. It may be inferred that at the molecular level, the bond strength is increased gradually by raising temperature when the force is kept constant. However, increase in force has a greater impact. To have a better clarity of the graphs, standard deviation error bars are just shown in Figure 3.12.

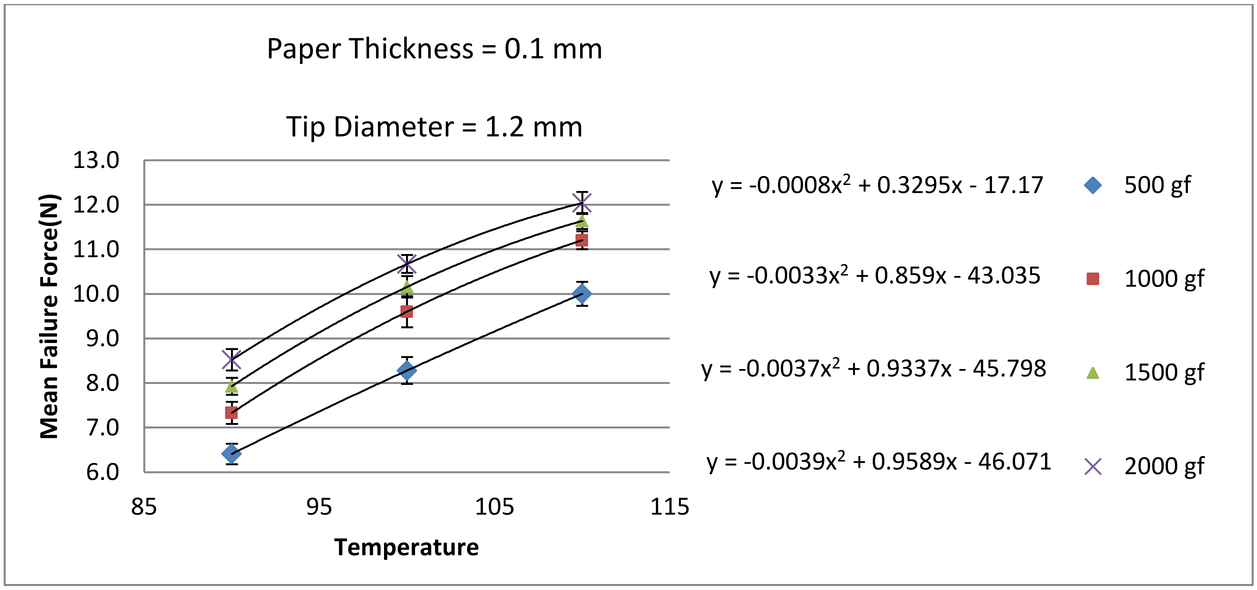


Figure 3.12: Mean failure force versus heat weld temperature for constant paper thickness (t=0.1 mm) and soldering iron tip diameter (D=1.2 mm) and force of 500gf, 1000gf, 1500gf and 2000gf.

Keeping all parameters constant and the same as in the previous case except the tip diameter, which was changed to 1.8 m, measured the bond strength. As illustrated in Figure 3.12, decreasing tip diameter has a direct impact on bond strength. Then effect of heat weld contact area can be seen comparing Figure 3.13 and 3.14. Increasing diameter from 1.8 mm to 2.4mm made a significant increase in the bond strength, though the graphs trend changed gradually from linear growth to polynomial trend.

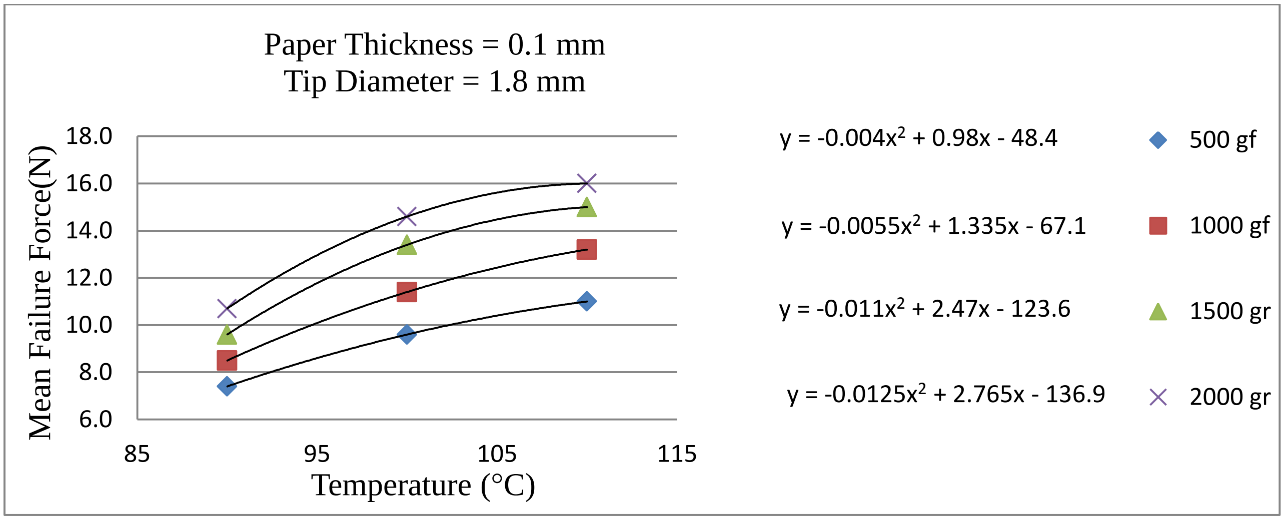


Figure 3.13: Mean failure force versus heat weld temperature for constant paper thickness (t=0.1 mm) and soldering iron tip diameter (D=1.8 mm) and force of 500gf, 1000gf, 1500gf and 2000gf.

According to Figure 3.14, an increase in tip diameter shows an asymptotic convergence towards the bond strength of about 20N. It may be conjectured that if the temperature is raised to melting point, the bond strength would decreased and the connection area would magnify this effect.

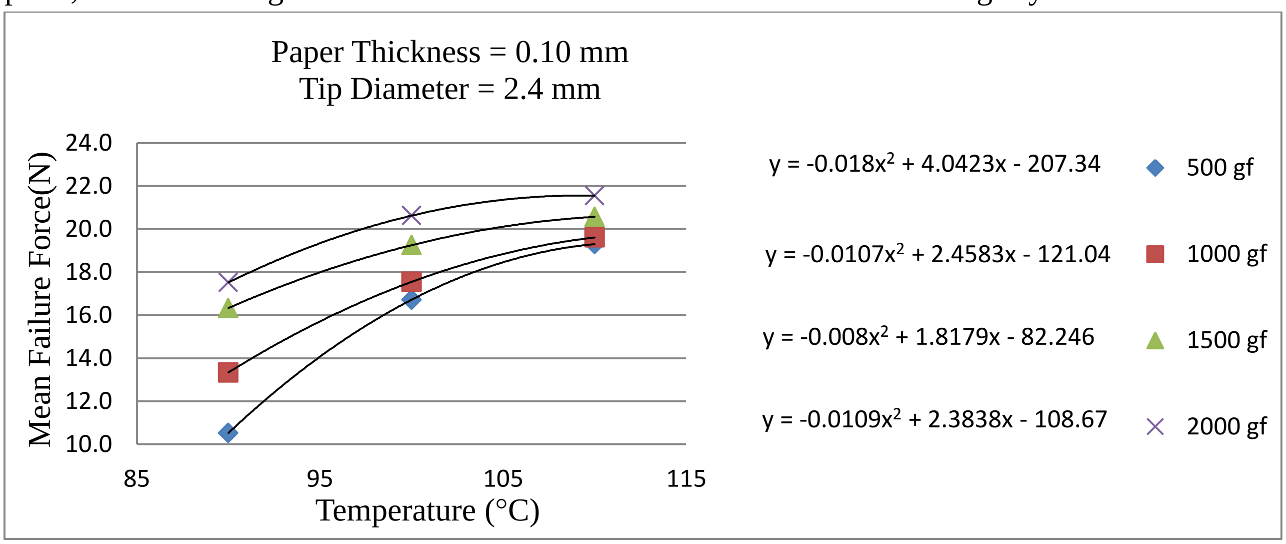


Figure 3.14: Mean failure force versus heat weld temperature for constant paper thickness (t=0.1 mm) and soldering iron tip diameter (D=2.4 mm) and force of 500gf, 1000gf, 1500gf and 2000gf.

The same experiments have been done on the hardwood paper with thickness of 0.18 mm. Figures 3.15, 3.16 and 3.17 show the bond strength behavior for the tip diameter of 1.2, 1.8 and 2.4 mm respectively. The rate of bond strength changes is less when compared to thinner paper (t=0.12 mm). However, there is still a convergence at 110 °C and tip diameter of 2.4 mm to about 17 N and that could be a possible explanation for the latest conclusion.

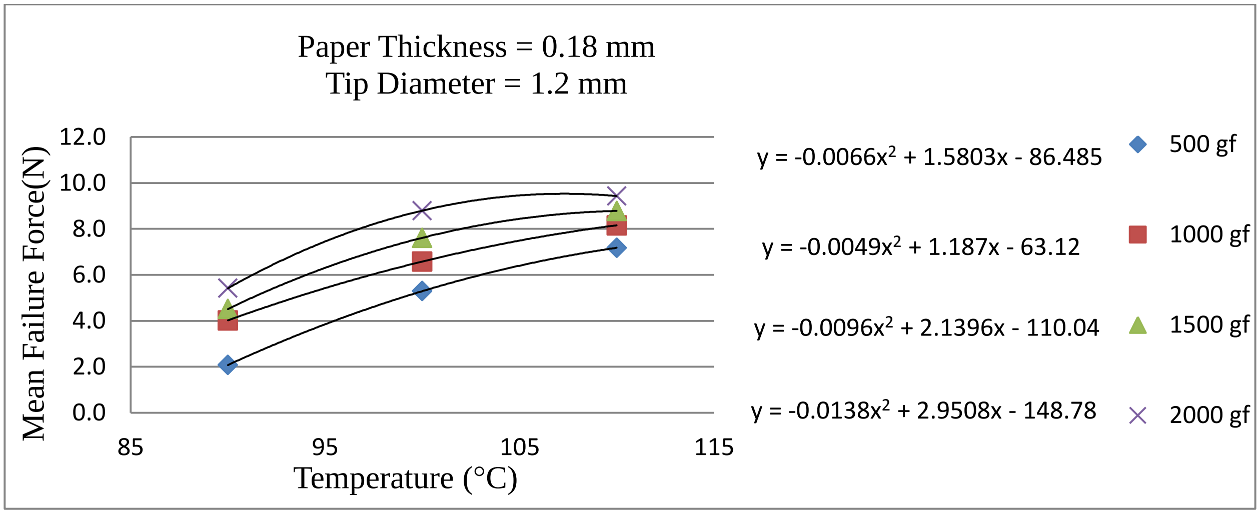


Figure 3.15: Mean failure force versus heat weld temperature for constant paper thickness (t=0.18 mm) and soldering iron tip diameter (D=1.2 mm) and force of 500gf, 1000gf, 1500gf and 2000gf.

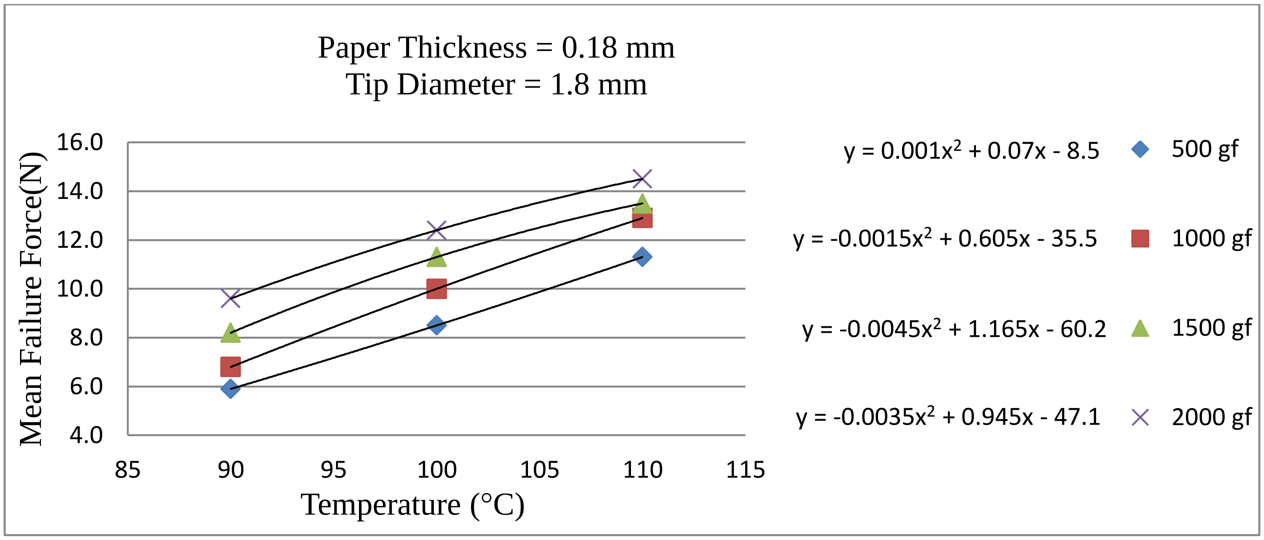


Figure 3.16: Mean failure force versus heat weld temperature for constant paper thickness (t=0.18 mm) and soldering iron tip area (D=1.8 mm) and force of 500gf, 1000gf, 1500gf and 2000gf.

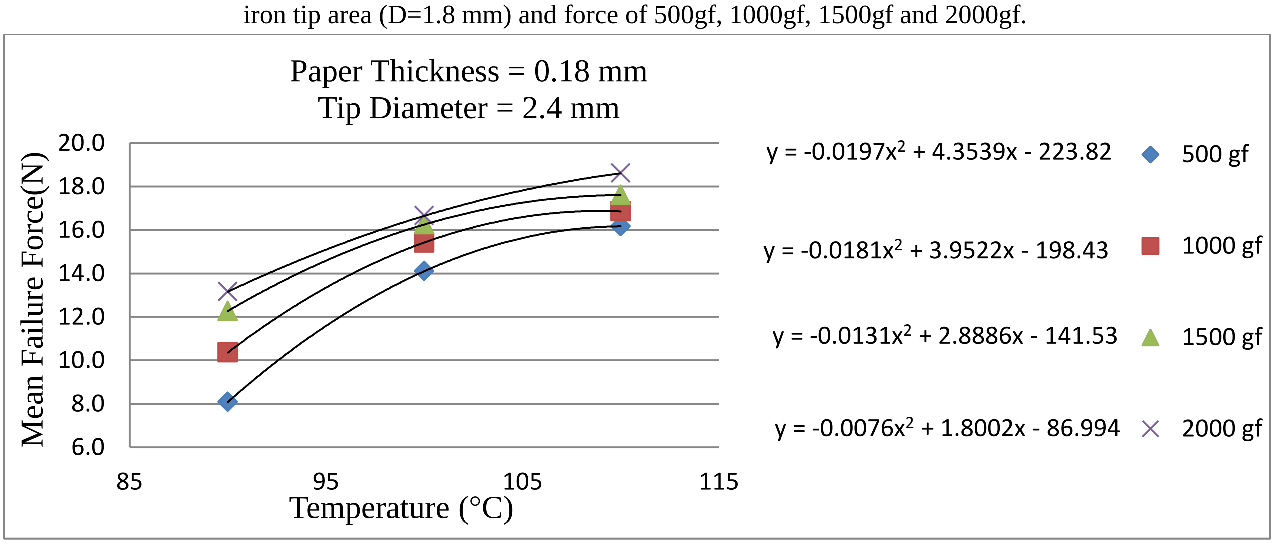


Figure 3.17: Mean failure force versus heat weld temperature for constant paper thickness (t=0.18 mm) and soldering iron tip area (D=2.4 mm) and force of 500gf, 1000gf, 1500gf and 2000gf.

Quantitative Simulation

Due to inadequate precision of the instruments, the experiments were conducted for a limited range of values of independent factors affecting bond strength. For example, the linear actuator used in the experiment could not provide the force increment of 100 gf, therefor the experiment was set for force increment of 500 gf. To have quantitative prediction of bond strength, a statistical analysis should be done in order to make a function of all significant variables.

The bond strength (σ) is a function of temperature (T), force (F), soldering iron diameter (D), and paper thickness (t):

$$\sigma = f(T, F, D, t) \tag{3.1}$$

Owing to the lack of sufficient data to provide reliable correlation estimates for all variables, the function is simplified by keeping the paper thickness constant and conducting all experiments for two paper thicknesses (t=0.1 mm and t=0.18 mm). At the end, we will have two series of equations for two paper thicknesses:

$$\sigma = f(T, F, D) \tag{3.2}$$

The correlation of bond strength and temperature for force of 500 gf can be taken from Figure 3.10, 3.11 and 3.12:

$$\sigma = f(T, D) = \begin{cases} -0.0008T^2 + 0.3295\mathrm{T} - 17.17 & for\ D = 1.2\ mm \\ -0.004T^2 + 0.98\mathrm{T} - 48.4 & for\ D = 1.8\ mm \\ -0.018T^2 + 4.023\mathrm{T} - 207.34 & for\ D = 2.4\ mm \end{cases} \tag{3.3}$$

A general form of equation can be written for bond strength as a function of temperature (T) and diameter (D) for the constant force of 500 gf:

$$\sigma = \mathrm{a(D)}T^2 + \mathrm{b(D)T} + \mathrm{c(D)} \tag{3.4}$$

Where:

$$a(D) = \begin{bmatrix} -0.0008 \\ -0.004 \\ -0.018 \end{bmatrix} \begin{matrix} for\ D = 1.2\ mm \\ for\ D = 1.8\ mm \\ for\ D = 2.4\ mm \end{matrix} \tag{3.5}$$

Figure 3.18 shows the correlation between a(D) and diameter (D):

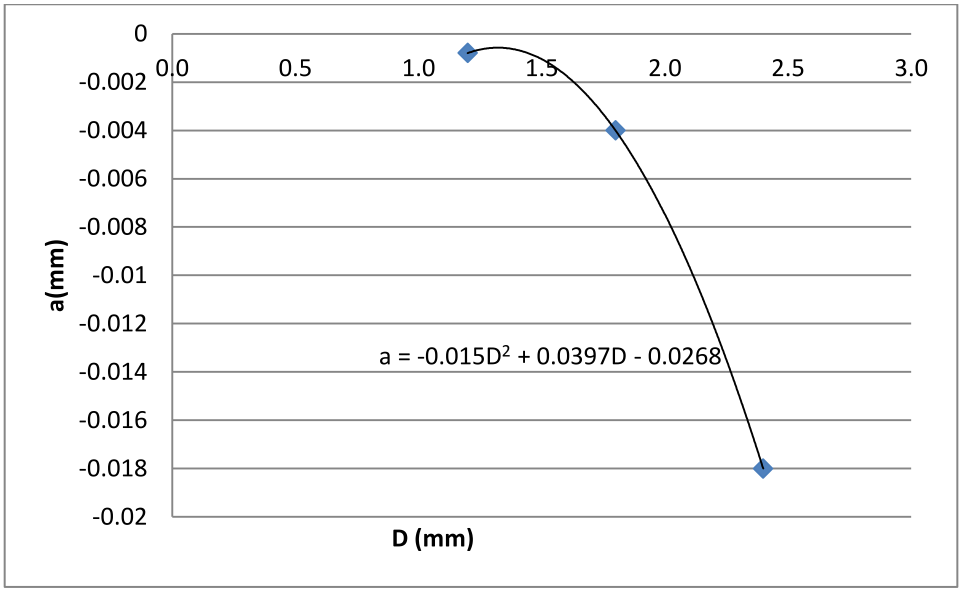


Figure 3.18: a(D) versus diameter (D)

A second degree polynomial equation was taken from the fitting line:

$$a(\mathrm{D}) = -0.015D^2 + 0.0397\mathrm{D} - 0.0268 \tag{3.5}$$

Also the related equation can be calculated for b(D) and c(D):

$$b(D) = \begin{bmatrix} 0.3295 \\ 0.98 \\ 4.023 \end{bmatrix} \begin{matrix} for\ D = 1.2\ mm \\ for\ D = 1.8\ mm \\ for\ D = 2.4\ mm \end{matrix} \tag{3.6}$$

$$c(D) = \begin{bmatrix} 17.17 \\ 28.4 \\ -207.34 \end{bmatrix} \begin{matrix} for\ D = 1.2\ mm \\ for\ D = 1.8\ mm \\ for\ D = 2.4\ mm \end{matrix} \tag{3.7}$$

Figure 3.19 and 3.20 shows the correlation between b(D) and c(D) and diameter:

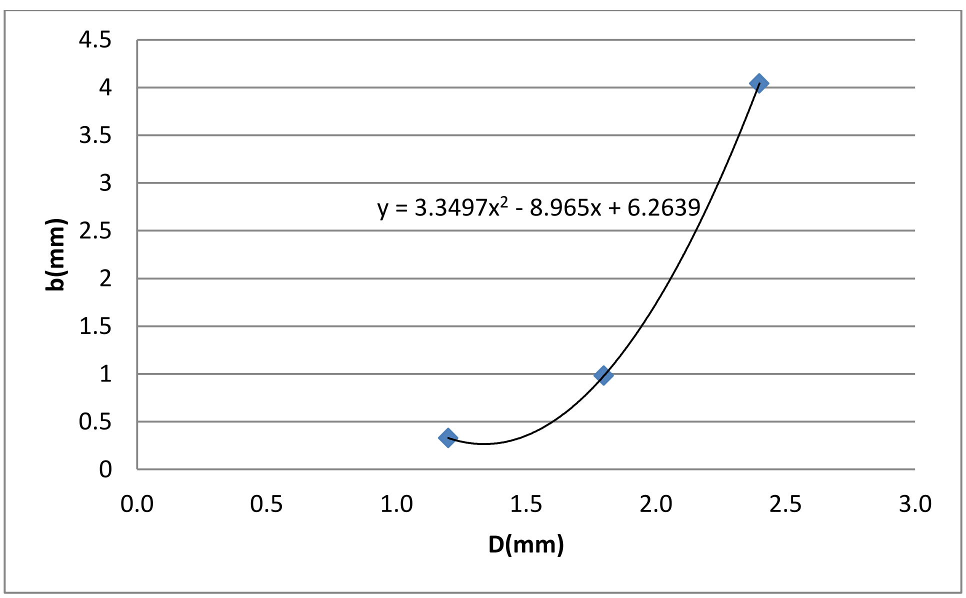


Figure 3.19: b(D) versus diameter

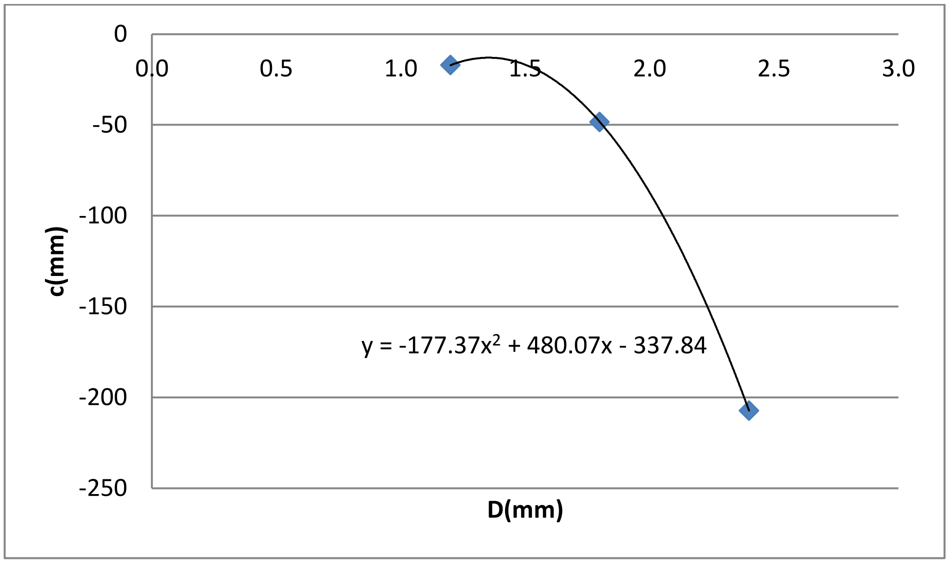


Figure 3.20: c(D) versus diameter

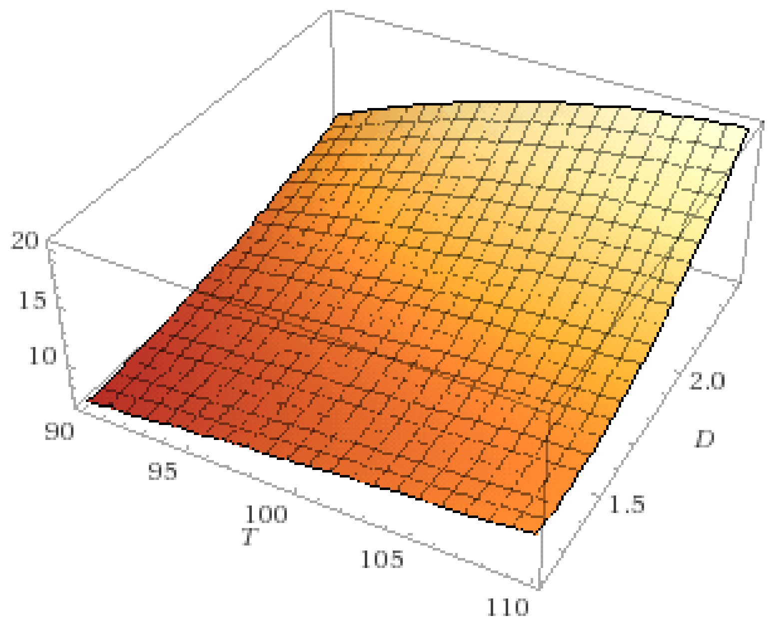


Figure 3.21: Bond strength (N) versus soldering iron temperature and soldering iron tip diameter for constant paper thickness of 0.1 mm and force of 500gf.

The related equations for b(D) and c(D) are also brought below:

$$\mathrm{b(D)} = 3.3497D^2 + 8.965\mathrm{D} + 6.2639 \tag{3.8}$$

$$\mathrm{c(D)} = -177.37D^2 + 480.07\mathrm{D} - 337.84 \tag{3.9}$$

Substituting the equations of (3.5), (3.8) and (3.9) in (3.4) gives a bond strength equation as a function of diameter and temperature for constant force of 500 gf:

$$\sigma = f(T, D) = (-0.015D^2 + 0.0397\text{D} - 0.0268)T^2 + (3.3497D^2 + 8.965\text{D} + 6.2639)\text{T} + (-177.37D^2 + 480.07\text{D} - 337.84) \quad (3.10)$$

Using this equation one can find the bond strength for any amount of the temperature and the soldering tip diameter for the force of 500 gf and paper thickness of 0.1 mm. The same analysis was done for the other amounts of force (1000gf, 1500gf and 2000gf), given below:

$$\sigma = f(T, D) = \begin{cases} (-0.015D^2 + 0.0397\text{D} - 0.0268)T^2 + (3.3497D^2 + 8.965\text{D} + 6.2639)\text{T} + (-177.37D^2 + 480.07\text{D} - 337.84) & for\ F = 500gf \\ (-0.0047D^2 + 0.0112D - 0.0103)T^2 + (1.0028D^2 - 2.3395D + 2.2971)T + (-45.331D^2 + 100.49D - 101.11) & for\ F = 1000gf \\ (0.0143D^2 - 0.0551D + 0.0418)T^2 + (-3.0394D^2 + 11.679D - 8.7041)T + (165.49D^2 - 626.15D + 467.27) & for\ F = 1500gf \\ (0.0142D^2 - 0.0568D + 0.0439)T^2 + (-3.0379D^2 + 12.124D - 9.2152)T + (165.36D^2 - 647.46D + 492.76) & for\ F = 2000gf \end{cases}$$

(3.11)

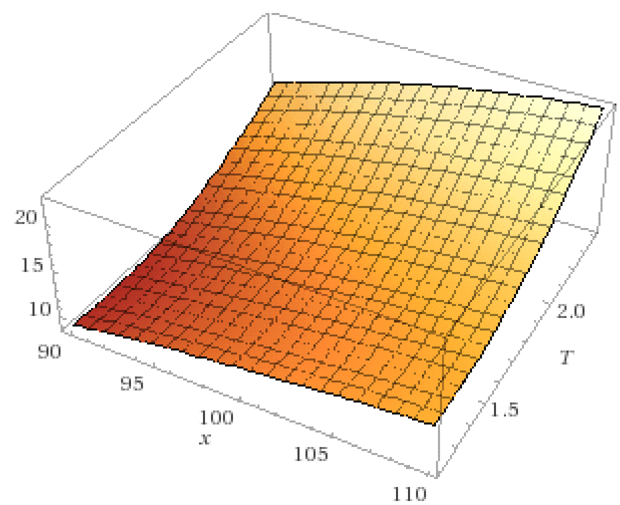


Figure 3.22: Bond strength (N) versus soldering iron temperature and soldering iron tip diameter for constant paper thickness of 0.1 mm and force of 1000gf.

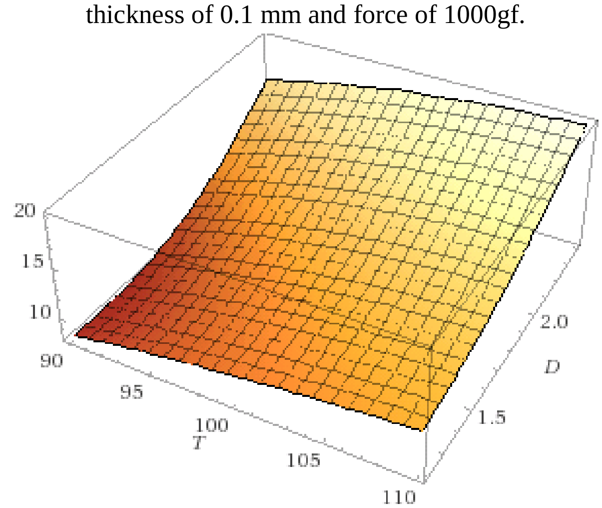


Figure 3.23: Bond strength (N) versus soldering iron temperature and soldering iron tip diameter for constant paper thickness of 0.1 mm and force of 1500gf.

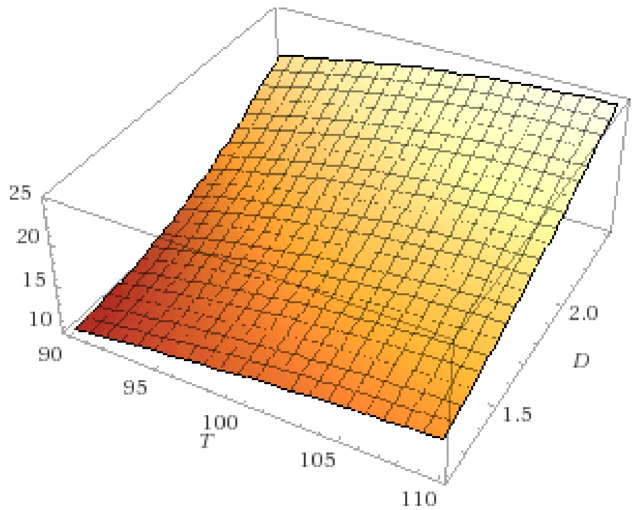


Figure 3.24: Bond strength (N) versus soldering iron temperature and soldering iron tip diameter for constant paper thickness of 0.1 mm and force of 2000gf.

The same equations can be obtained by keeping the temperature constant and having a series of equations for the bond strength as a function of the force (F) and the diameter (D):

$$\sigma = f(F,D) = \begin{cases} (-3e^{-6}D^2 + e^{-5}\mathrm{D} - 8e^{-6})F^2 + (0.0093D^2 - 0.0279\mathrm{D} + 0.0223)\mathrm{F} + (-1.1026D^2 + 4.8018\mathrm{D} + 1.2294) & for\ T = 90^{\circ}C \\ (e^{-6}6D^2 - 3e^{-6}D + 2e^{-6})F^2 + (-0.0068D^2 + 0.0226D - 0.0137)F + (11.233D^2 - 32.846D + 29.976) & for\ T = 100^{\circ}C \\ (3e^{-6}D^2 - 8e^{-6}D + 5e^{-6})F^2 + (-0.0133D^2 + 0.0452D - 0.0317)F + (16.045D^2 - 48.934D + 44.197) & for\ T = 110^{\circ}C \end{cases} \tag{3.12}$$

Equation 3.11 and 3.12 enables the users to find out the strength attachment of various amount of temperature, force, heat weld diameter for two paper thickness of 0.1. Equation 3.13 represents the bond strength as a function of the force (F) and the diameter (D) for constant paper thickness of 0.18 mm.

$$\sigma = f(F,D) = \begin{cases} (-4e^{-6}6D^2 + 2e^{-5}D - 1e^{-5})F^2 + (0.0128D^2 - 0.0442\mathrm{D} + 0.0393)\mathrm{F} + (-7.2754D^2 + 30.251\mathrm{D} - 25.754) & for\ T = 90^{\circ}C \\ (-3e^{-7}6D^2 - 3e^{-7}D - 1e^{-7})F^2 + (-0.0008D^2 + 0.0042D - 0.0012)F + (3.8633D^2 - 7.006D + 6.8936) & for\ T = 100^{\circ}C \\ (2e^{-6}D^2 - 6e^{-6}D + 4e^{-6})F^2 + (-0.0054D^2 + 0.0183D - 0.0118)F + (3.2165D^2 - 3.6127D + 5.8314) & for\ T = 110^{\circ}C \end{cases} \tag{3.13}$$

3.4 Conclusion

In this experiment, I made an overfitting model to explain the observations in terms of possible experimental results that provided us a rough estimation of attachment strength under different circumstances. More precise estimation needs more advanced experimental device. The possible error in measuring device or external effects, such as ambient temperature fluctuation, caused imprecise results. According to three dimensional graphs, increasing temperature and heat welding area and force would increase the paper-polymer bond strength. Results show that for higher pressure, heat welding area has a greater impact on paper-polymer bond strength rather than heat weld temperature, though there is a limit on amount of applied pressure. For larger pressure of 2000gf the bond strength would converge to a certain amount for all amounts of other variables.

Chapter 4 – Paper Folding Simulation

4.1 Objective

The ultimate goal of this project is to create the products using plastic shrinkage method. Any origami patterns has its own geometry which consists of one or more folding angles, therefore folding angles should be characterized precisely in order to fold any pattern accurately and get a descent result. To obtain this goal, a precise folding angle simulation is necessary.

4.2 Experimental Studies

Some significant factors are recognized affecting the folding procedure such as attachment distance to fold line, heating temperature, paper thickness among others.

4.2.1 Effect of Polystyrene Attachment Distance to Fold Line on Fold Angle

Considering the point that the polystyrene pieces shrank to 40% of their original size regardless of their size, orientation or shape and based on some experiments, the hypothesis is that the first significant factor which determines the folding angle could be the polystyrene attachment distance with fold line. Since consistent shrinking of the polymer is expected, the correlation of folding angle and polymer attachment distance can be calculated, as illustrated in Figure 4.1:

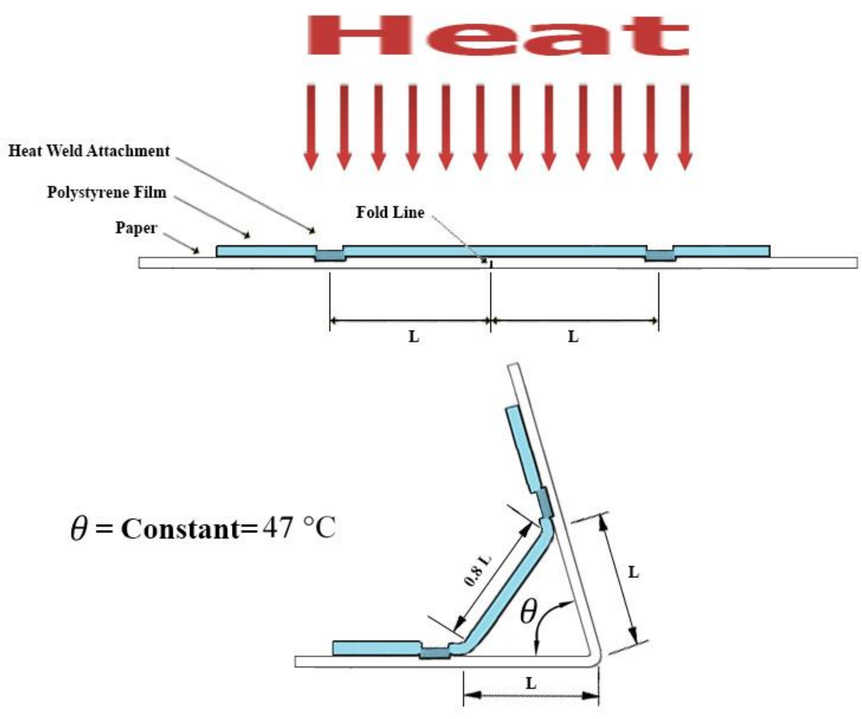


Figure 4.1: Theoretically the folding angle is independent of polystyrene attachment distance to fold line.

The possible solution to change the folding angle is to move the folding line from the middle of two attachment points. This solution provides a small change in folding angle while it theoretically has some limitations regarding to the ratio of larger side of paper to smaller side. Higher ratio caused bending on one or two sides of paper.

This theory was not proved by repeating this experiment for the different distance of polystyrene attachment and folding line. The polystyrene behaviour is completely different when it is connected to the paper. It concludes to the fact that there are some other factors which affect the folding angle. Also the results for the constant polystyrene distance were inconsistent. General results show smaller distance between polymer attachment points results in a wider folded angle, meaning the polymer shrinks less.

4.2.2 Effect of Temperature on Fold Angle

Anthony Hyunkyoo and Zendai Kashino have conducted a series of experiments in the Pulp and Paper Centre to characterize the temperature-dependent behaviour of the polystyrene when it is attached to paper:

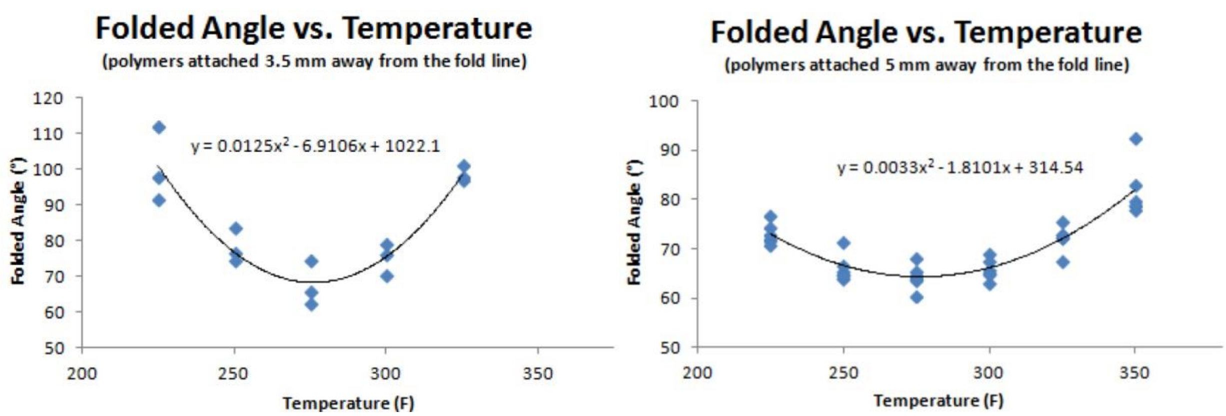


Figure 4.2: Fold angle dependence on temperature with polymers of length 3.5mm (left) and 5mm (right)

The results show that there is a minimum fold angle at 275°F in the oven, whether the polymer attachment distance was 3.5 mm from the fold line or 5 mm from the fold line. The decrease in the folded angle up to 275° F can be explained by only partial shrinkage of polymer occurring due to low heat up to that point. However, increasing angle at 300°F and above is due to factors such as fluctuation in the heat element power inside the oven, and weakening of paper-polymer soldered joint in rapid shrinkage of high temperature. It is also concluded that the tension at the paper-polymer soldered joints causes the temperature dependent behaviour of paper-polymer composite to be different from that of just the polymer alone.

4.2.3 Effect of Paper Thickness on Fold Angle

All types of paper and paperboard have a specific stiffness (or bending stiffness), which is the degree to which paper or board resists bending when subjected to a bending force in its intended

use. Considering paper bending stiffness definition, any type of paper or cardboard with different thicknesses needs a specific amount of bending moment to bend.
A measurement has been done on the polystyrene sheets used in this project to determine the maximum force they can apply. Some rectangular pieces of polystyrene with dimension of 15mmx30mm, 15mmx50mm, and 15mmx70mm were cut. The test method covers a procedure to measure the maximum load that a polystyrene piece can apply while it is shrinking (Figure 4.3).

They are fixed from one side vertically and various loading weights were attached to the other side of the plastic pieces. A heat gun was used to heat the polystyrene pieces uniformly. The maximum load that polystyrene pieces can pull up while they are shrinking to 40% of their original size was approximately 100g (1N) regardless of the specimens' size. The higher applied load can be carried to 130g but it caused polymer pieces elongation.

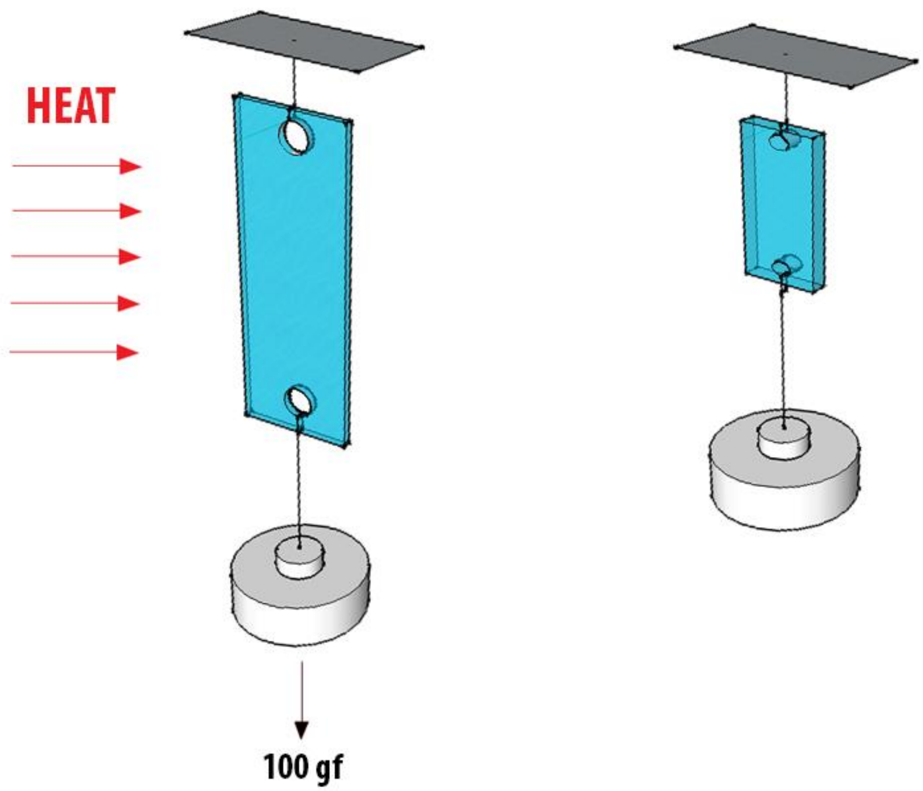


Figure 4.3: Experiment to measure the force of polymer shrinking

Due to the limited force the polystyrene can apply on the paper, and in order to guide the folding direction, the paper and cardboard need to be creased. Some experiments were done for the cardboard with the thicknesses of 10 pt., 12 pt., 14 pt., 18 pt. and 20 pt. All the cardboards were provided by Cascades. To predict the folding angle for all different paper thicknesses, all the cardboards thicknesses were increased by creasing to 5 pt. (0.127 mm) (Figure 4.4). Adjusting the force units in FC2250-180 enables users to change the cutting depth on the paper and cardboard.

Therefore, the paper thickness is the same on the creased line and the same polystyrene attachment distance was used to make the certain fold angle for all paper thicknesses.

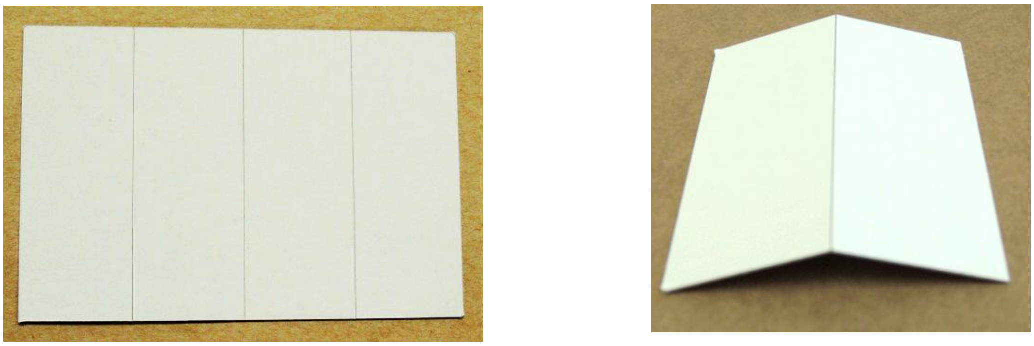


Figure 4.4: The creased cardboard

The cutting depth can be determined based on both the final structure strength and the power of polystyrene while it is shrinking. A deeper crease makes the folding easier; however, it results in a weaker final product. It can be adjusted based on the product application, though the attached pieces of polystyrene act as a support for the structures so that they can keep the angles constant and increase the strength of product structure.

Figure 4.5, Figure 4.6 and Figure 4.7 demonstrate how precise angles can be built into the products which are made from cardboards with different thicknesses.

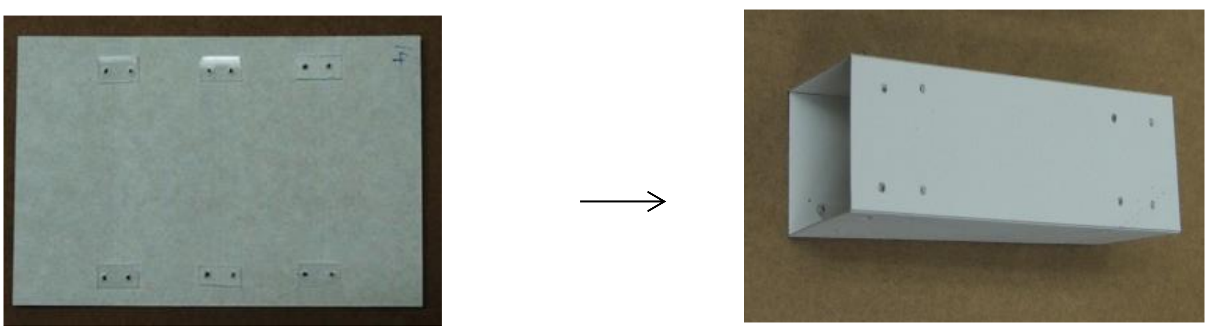


Figure 4.5: Precise folding angle is used to make a cardboard box with the cardboard with thickness of 14 pt.

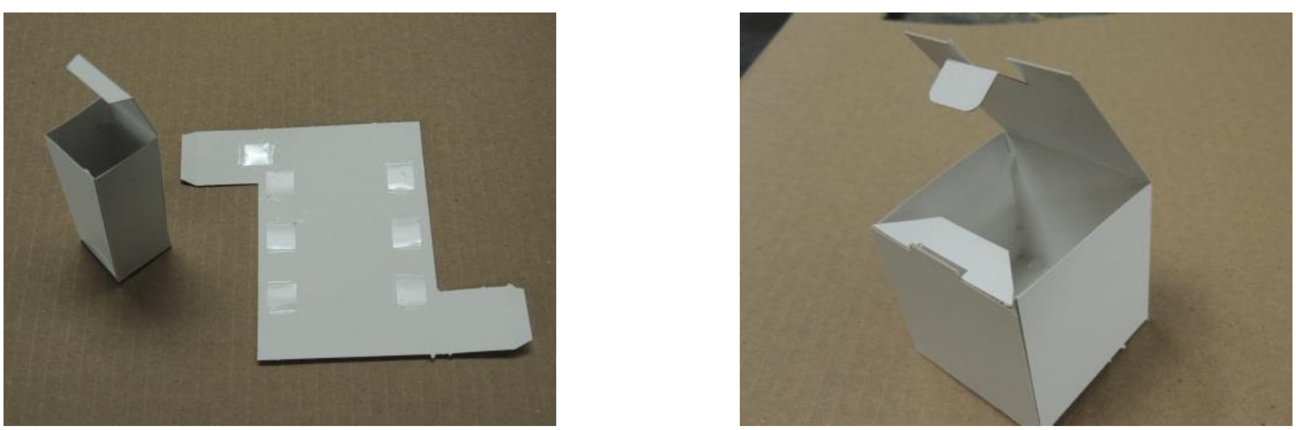


Figure 4.6: Precise folding angle is used to make a cardboard box with cardboard thickness of 12 pts.

* In the US, card stock thickness is usually measured in points which give the thickness of the sheet in thousandths of an inch. For example, a 10 pt. card is 0.010 in (0.254 mm) thick.

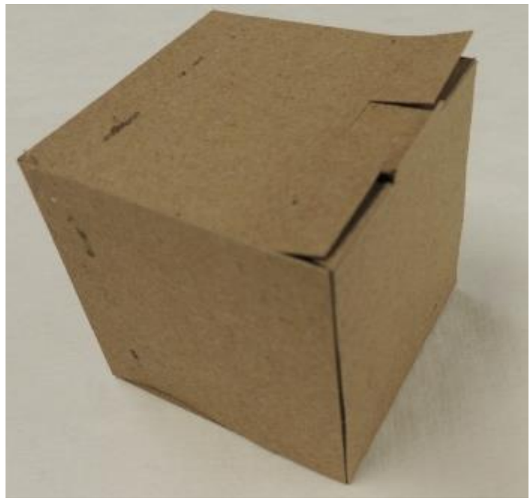


Figure 4.7: Precise folding angle is used to make a paper box with thickness of 10 pts.

The linerboard with single faced corrugated board was tested and the result is shown in Figure 4.8:

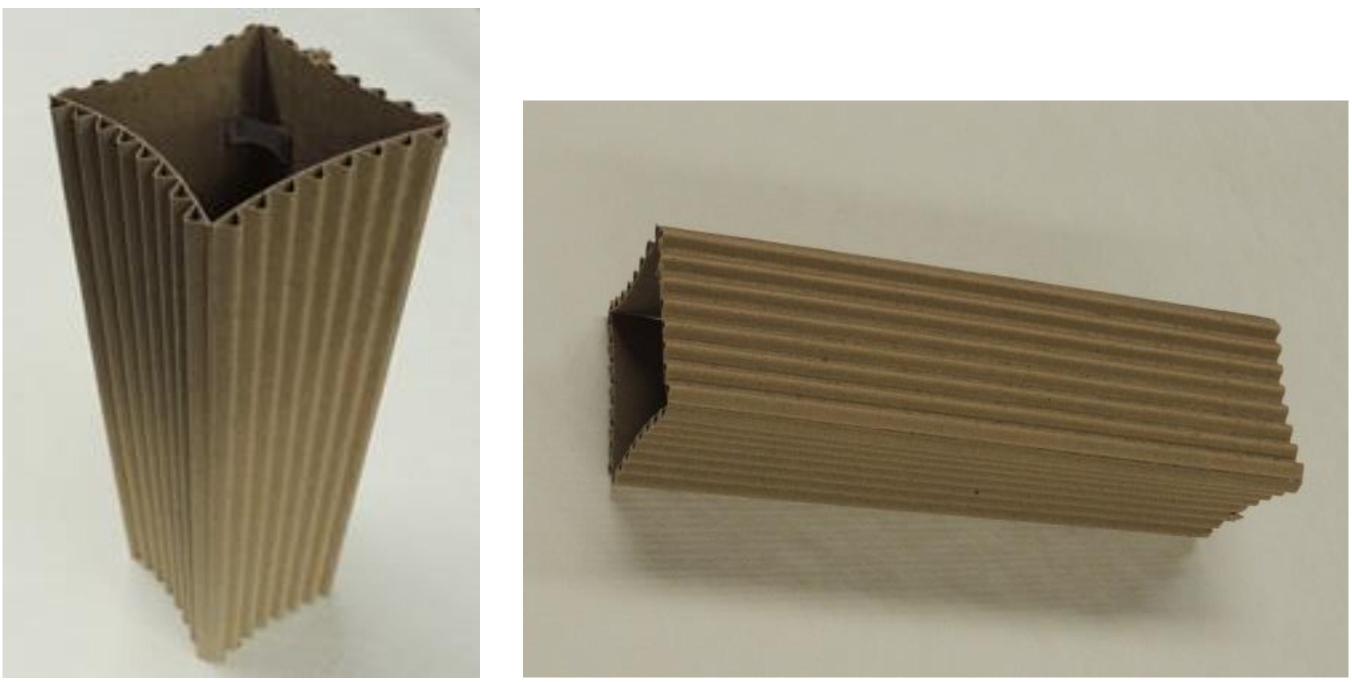


Figure 4.8: Folded linerboard with single faced corrugated board

Chapter 5 – Products and Applications

The purpose of the research is to create paper products that can replace various unsustainable plastic products. Plastics are used in a vast range of products due to their relatively low cost and ease of manufacture, and they have already displaced many paper products. Paper products will be able to compete with plastic products if they can be produced at a low cost and easy manufacturing process in order to make a strong structure, with the added benefit that paper products are green and recyclable. Origami patterns have a high potential of making aesthetic and strong paper products while using shrinkage plastic methods can ease the process of paper structures making. The combination of origami and our technique can produce different applications that are explained and illustrated below:

5.1 Various Decorative Design

Various types of snowflakes can be made using this technique. The snowflake pattern is drawn in AutoCAD while the creasing line, polymer pieces location and heat weld points are defined in different layers in AutoCAD (Figure 5.1).

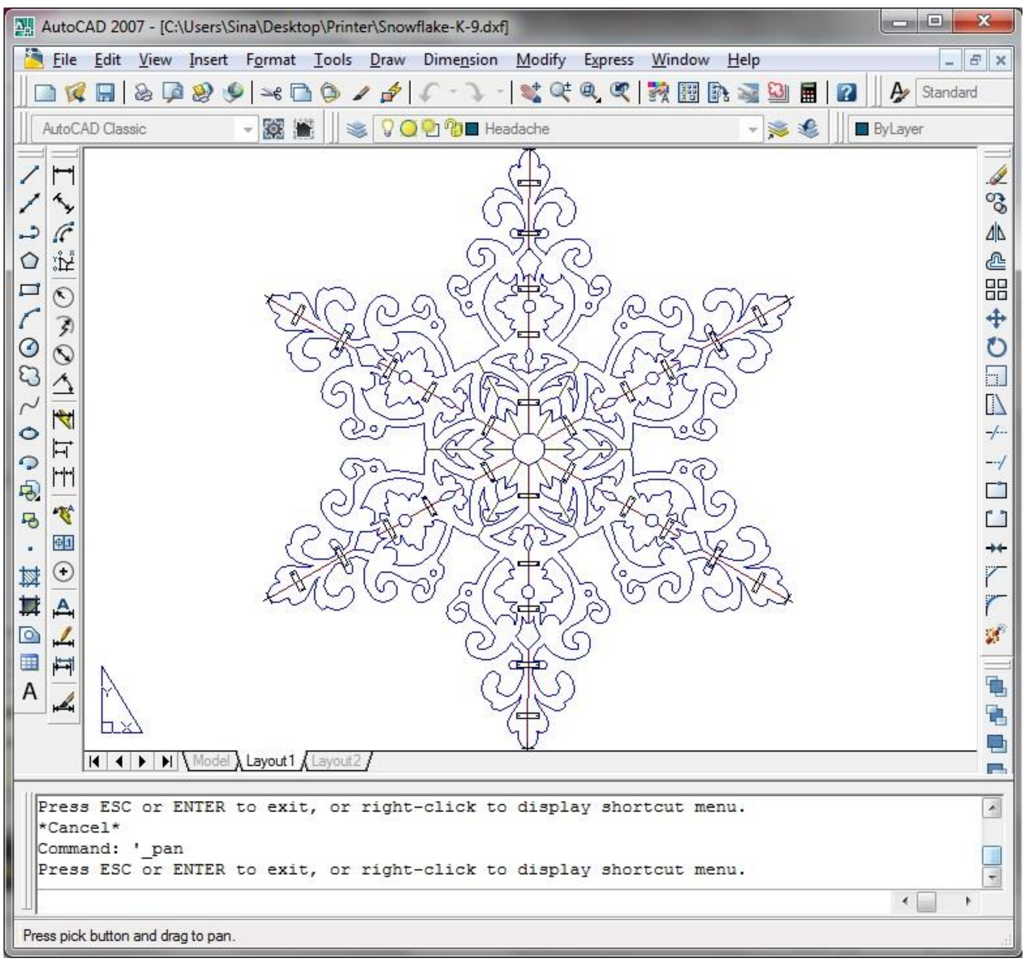


Figure 5.1: An AutoCAD cut/crease pattern of snowflake with layer in different color.

Then the paper and polystyrene sheet are cut, creased and welded together using FC2250-180 and the result is a flat piece of paper with small pieces of polymer attached to it (figure 5.2).

Figure 5.2: The cut and creased paper snowflake with polymer pieces attached to it.

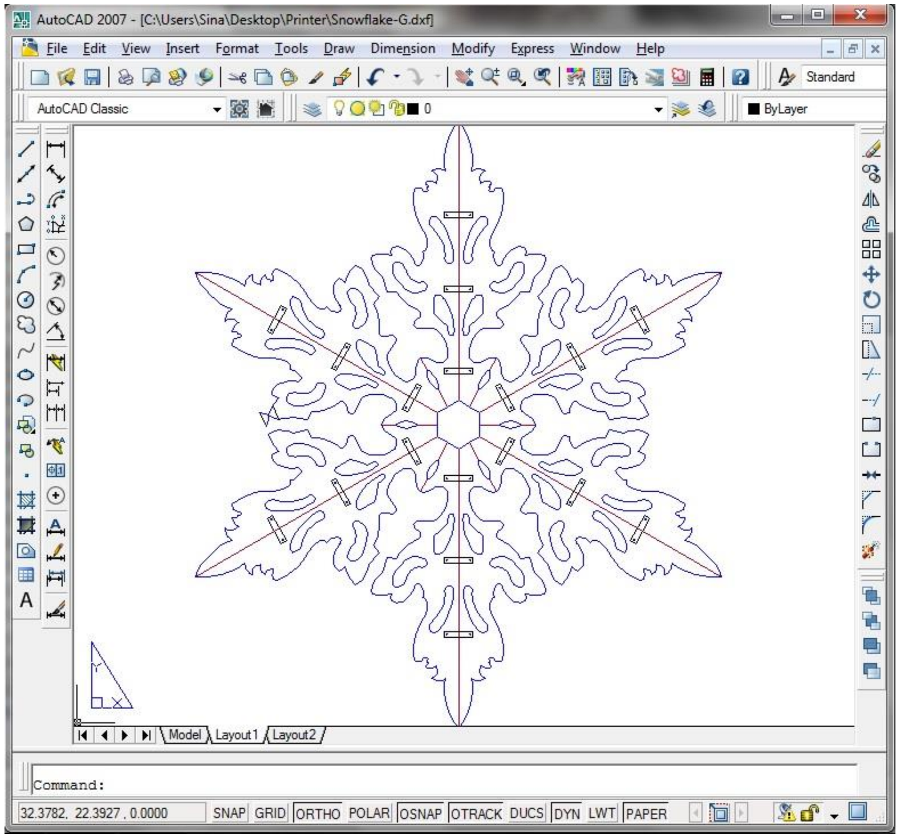
The final product is then placed in an oven (or toaster oven) which is preheated to approximately 120°C. The flat snowflake transforms to a 3 dimensional snowflake in approximately 15 seconds. Figure 5.5 shows the folding process in the oven. The real video is available on $YouTube$[1]. Additional drawings and photos of different snowflakes are shown in Figure 5.6, 5.7, 5.8, and 5.9:

1 URL to "Pulp and Paper Centre, UBC, 3D Snowflake", 2013 https://www.youtube.com/watch?v=k_jqVxPhI5g

Figure 5.3: 3D snowflake (featured on the cover of INGENUITY, Fall 2013/Winter 2014).

Figure 5.4: A close view of the attached polystyrene.

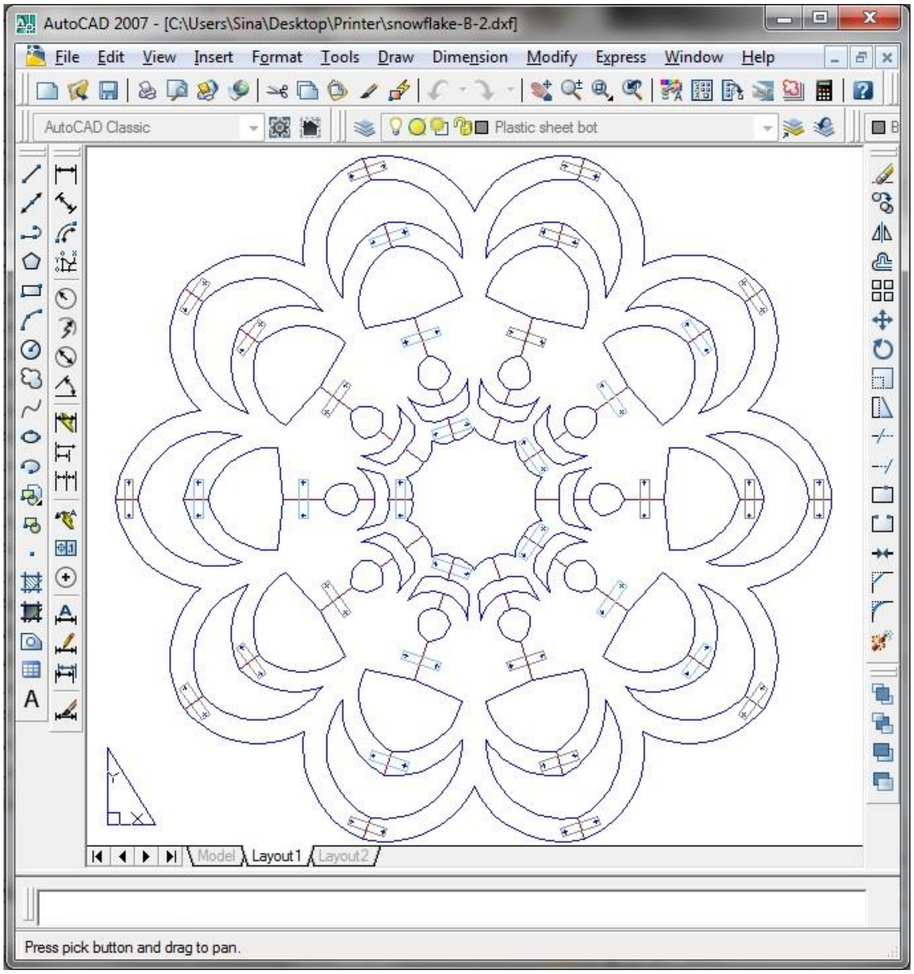
Figure 5.5: Snowflake folding process in eight frames.



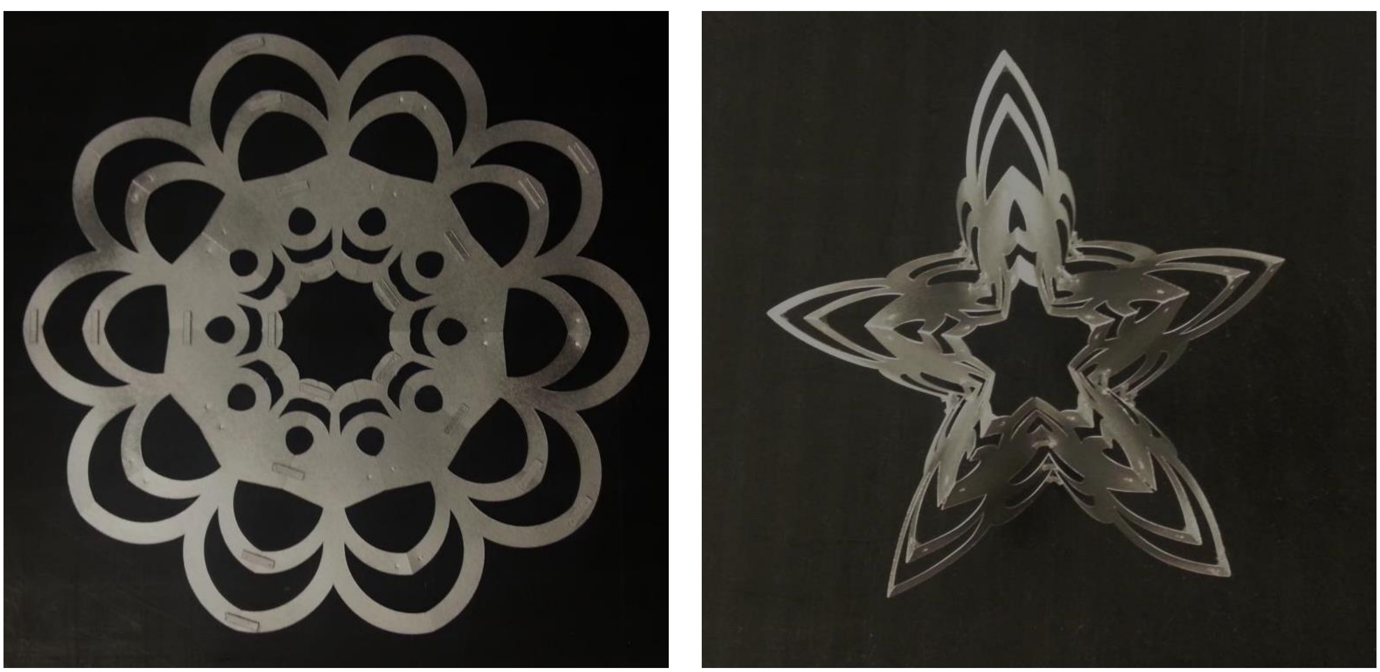
(a)

(b)

Figure 5.6: AutoCAD drawing of a snowflake (a) and the folded snowflake photo by Martin Dee (b).

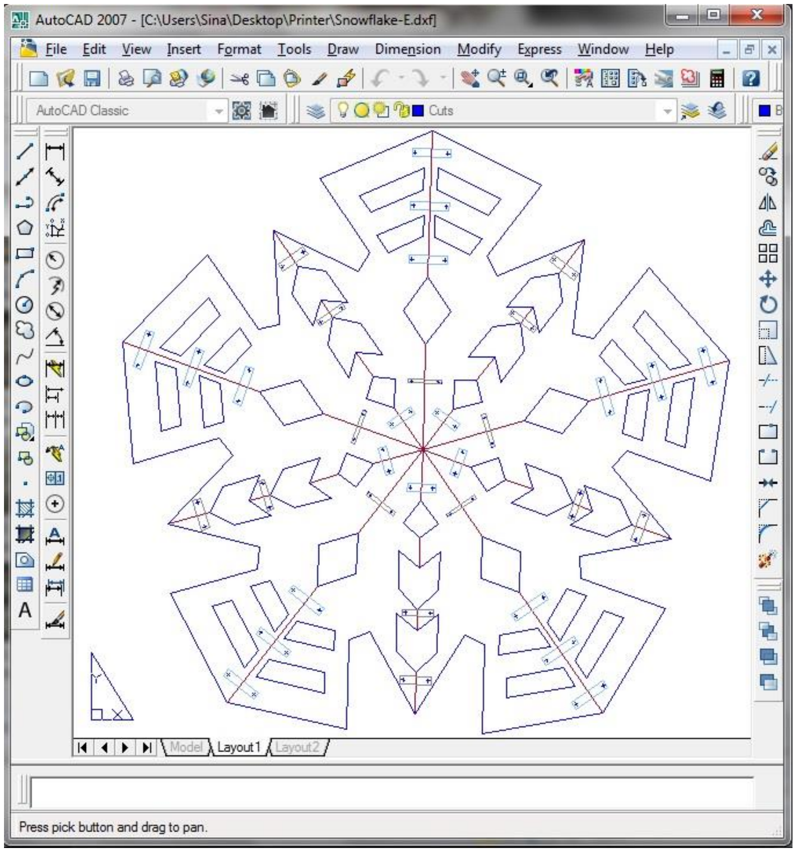


(a)



(b)

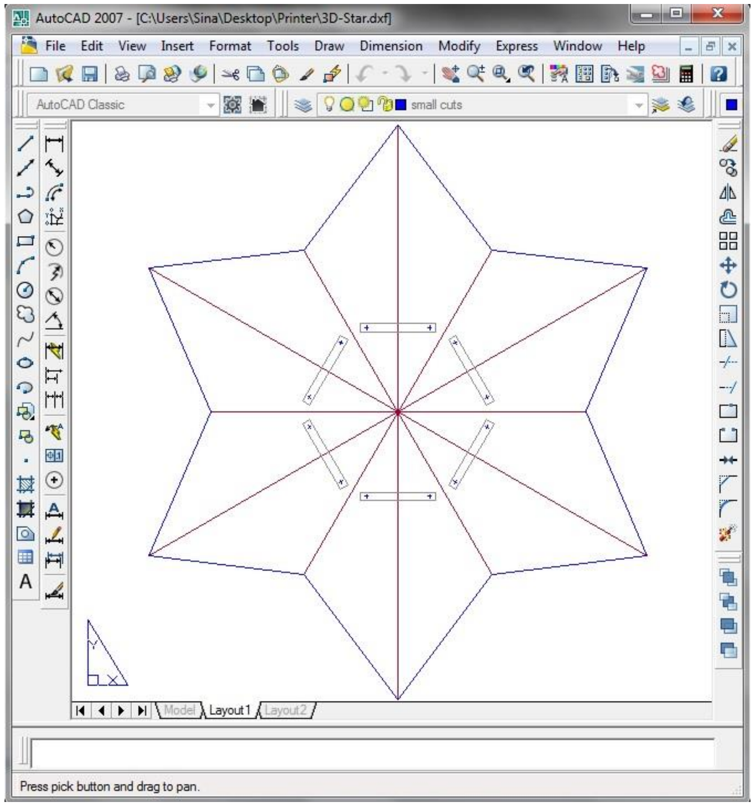
Figure 5.7: AutoCAD drawing of a snowflake (a) and the folded snowflake (b).



(a)

(b)

Figure 5.8: AutoCAD drawing of a snowflake (a) and the folded snowflake (b).



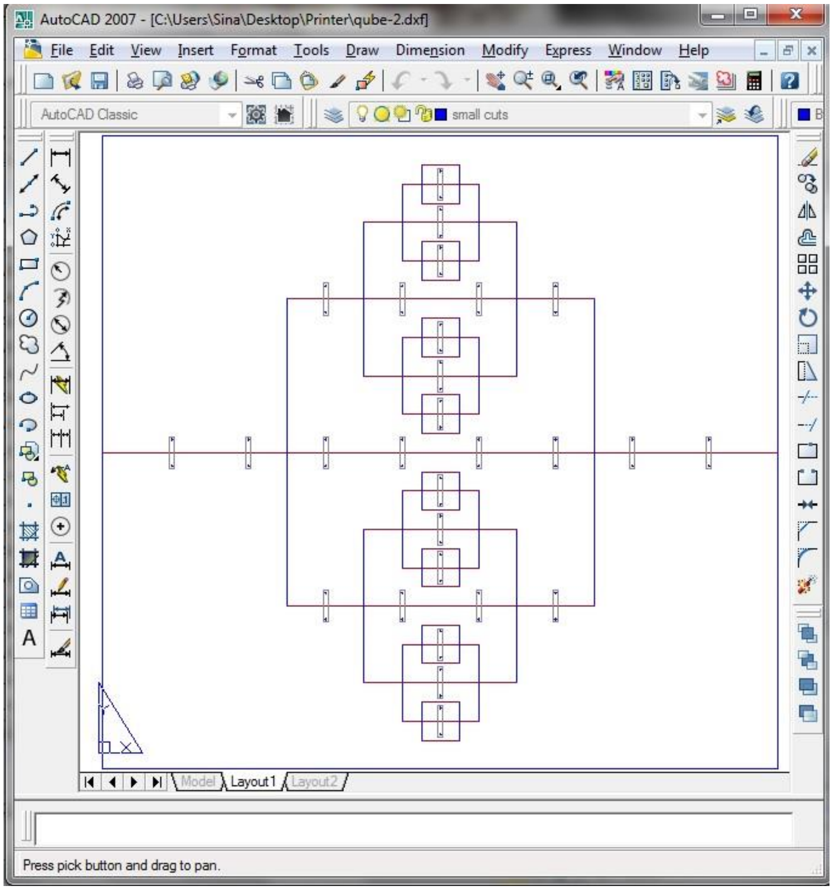
(a)

(b)

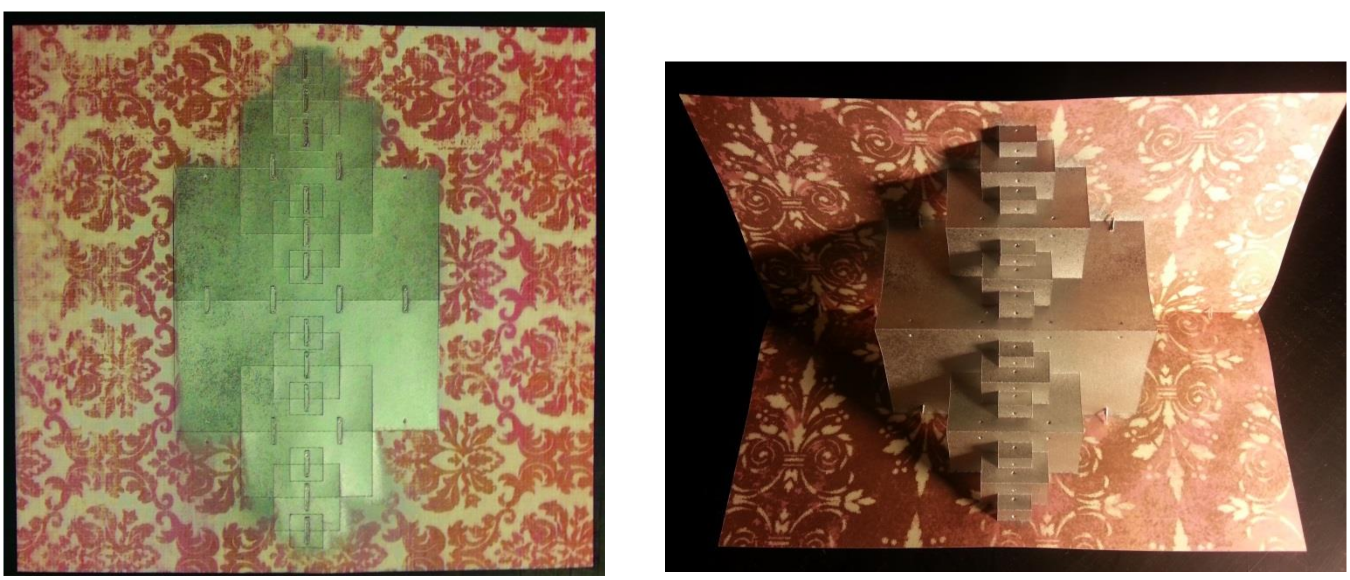
Figure 5.9: AutoCAD drawing of a star (a) and the folded star (b).

5.2 Pop-Up Greeting Card

Different pop-up greeting card designs have been made using the shrinkage method

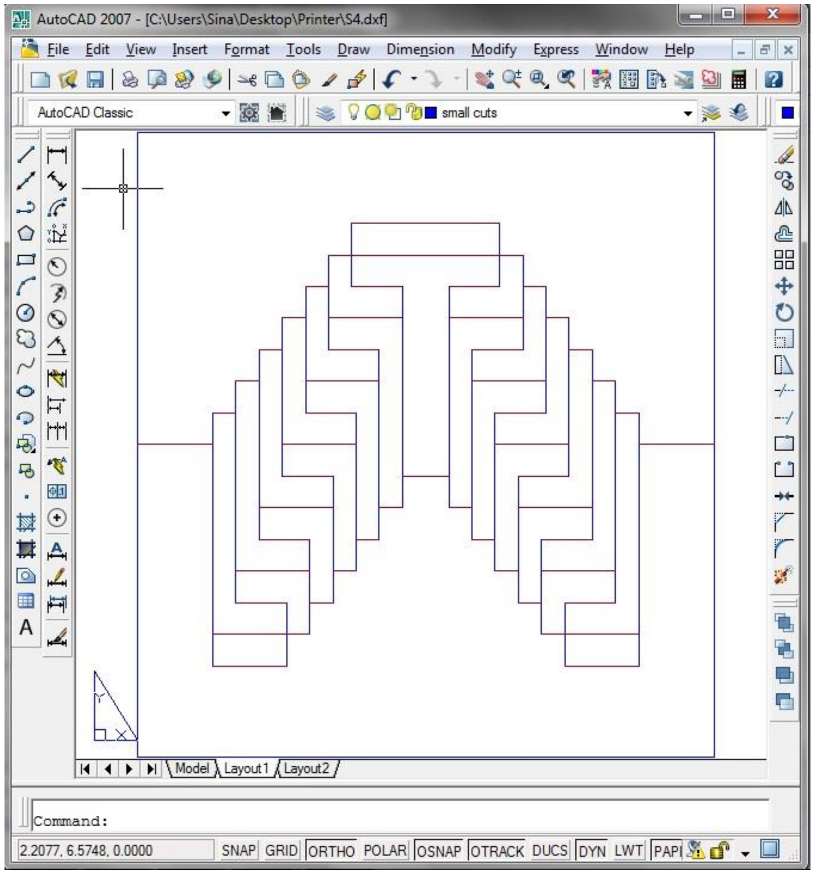


(a)

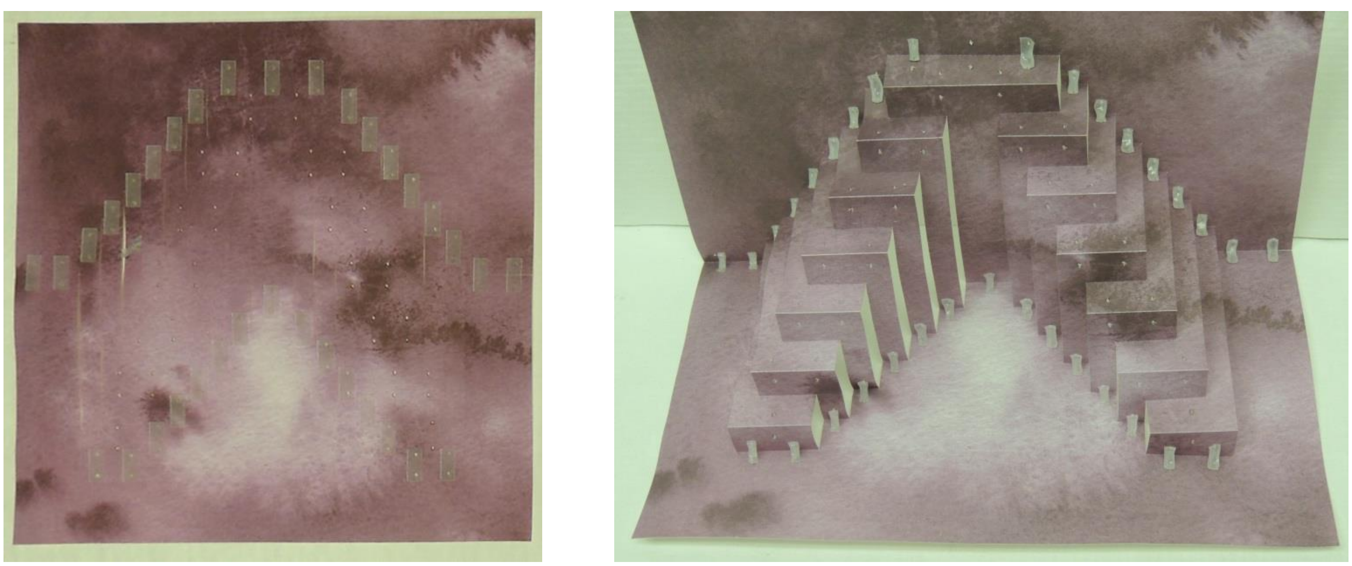


(b)

Figure 5.10: AutoCAD drawing of a pop-up greeting card (a) and its unfolded and folded model (b).

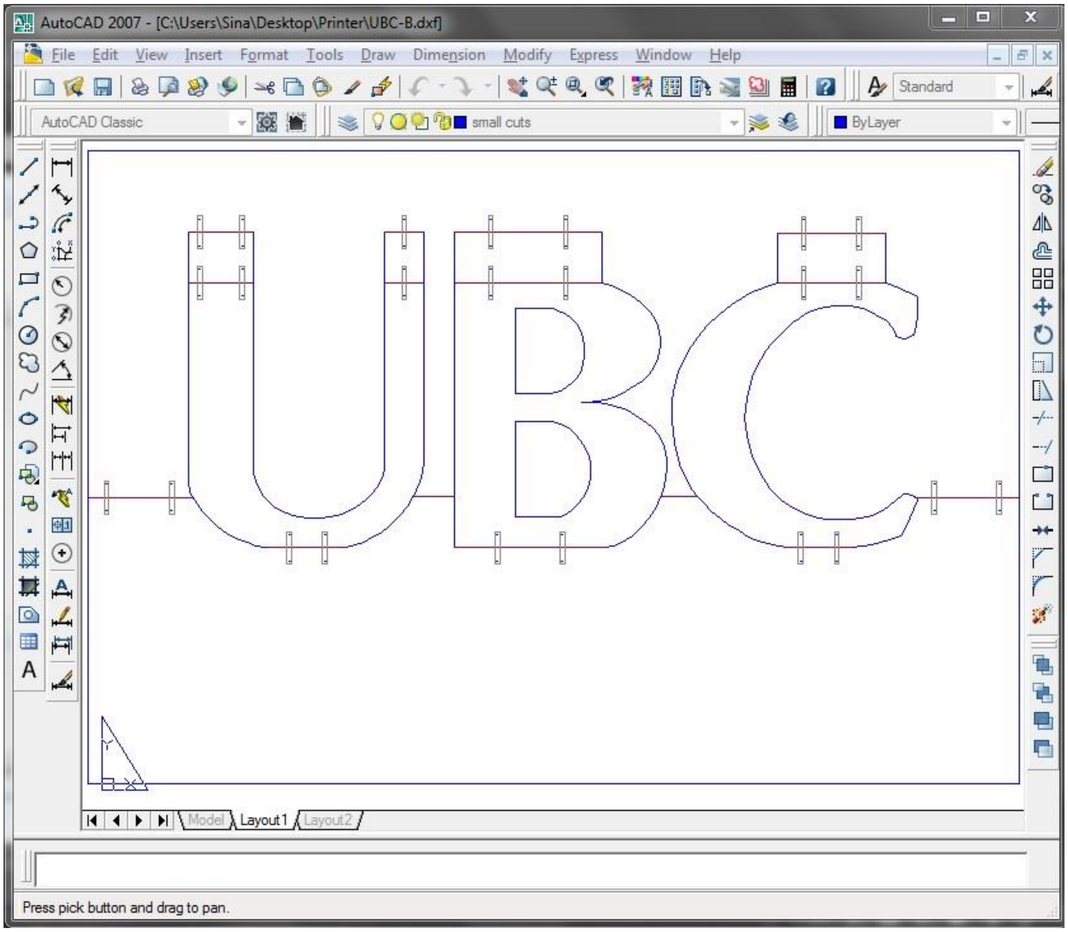


(a)



(b)

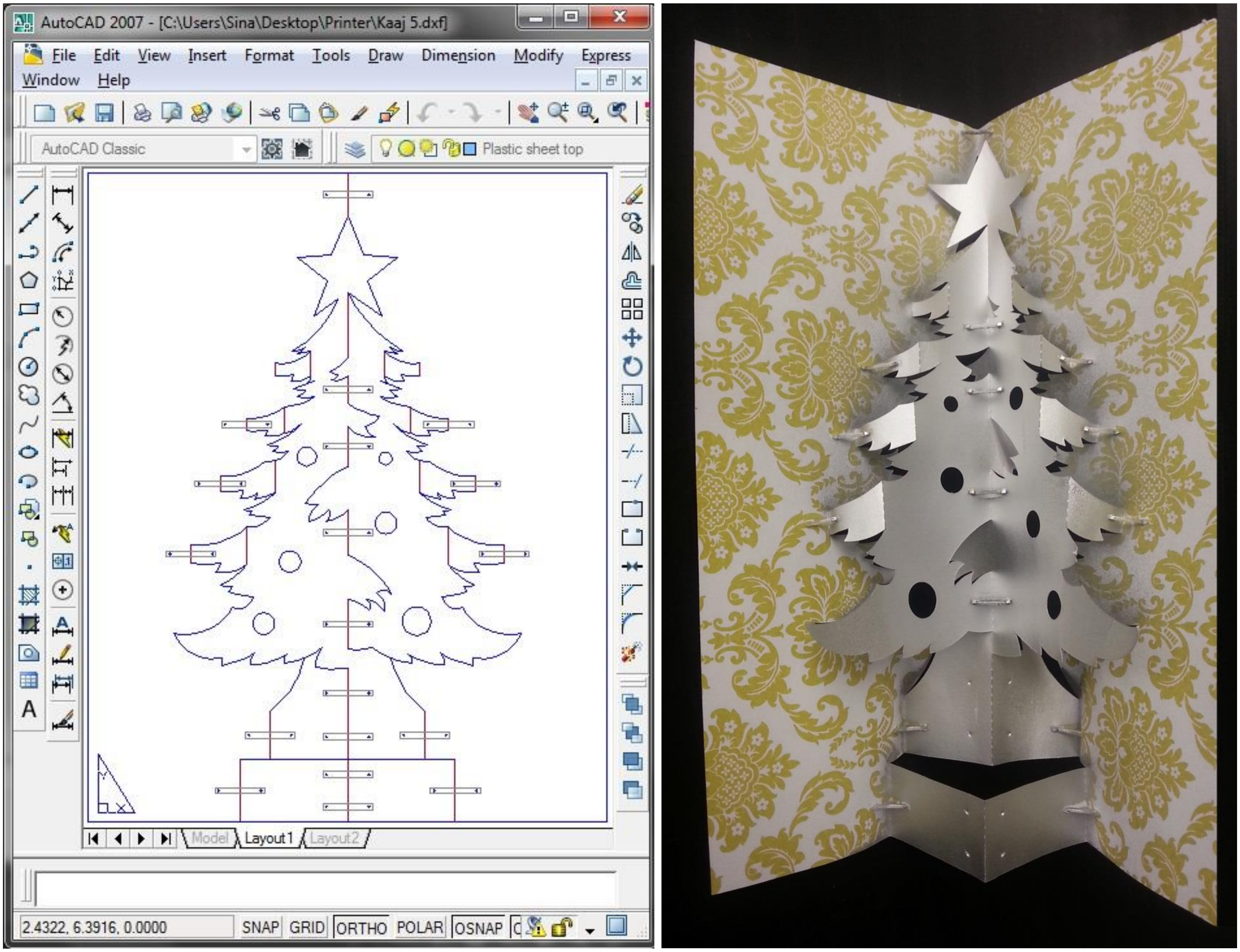
Figure 5.11: AutoCAD drawing of a pop-up greeting card (a) and its unfolded and folded model (b).



(a)

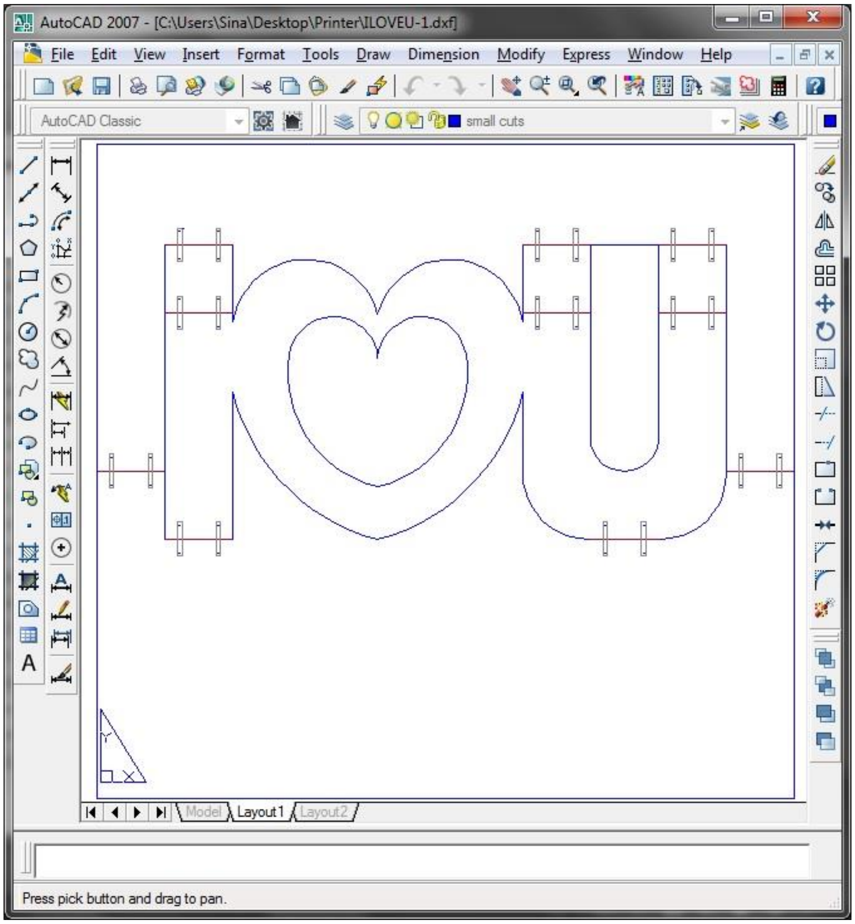
(b)

Figure 5.12: AutoCAD drawing of a pop-up greeting card (UBC logo) (a) and the folded model (b).



(a) (b)

Figure 5.13: AutoCAD drawing of a pop-up greeting card (Christmas tree) (a) and the folded model (b).



(a)

(b)

Figure 5.14: AutoCAD drawing of a pop-up greeting card (I love you) (a) and the folded model (b).

5.3 Lampshade

Using auto-origami method enables users to easily make their own lampshade by applying heat, such as from a hair dryer. Several lampshade designs and the final products are shown in Figures 5.15 to 5.19:

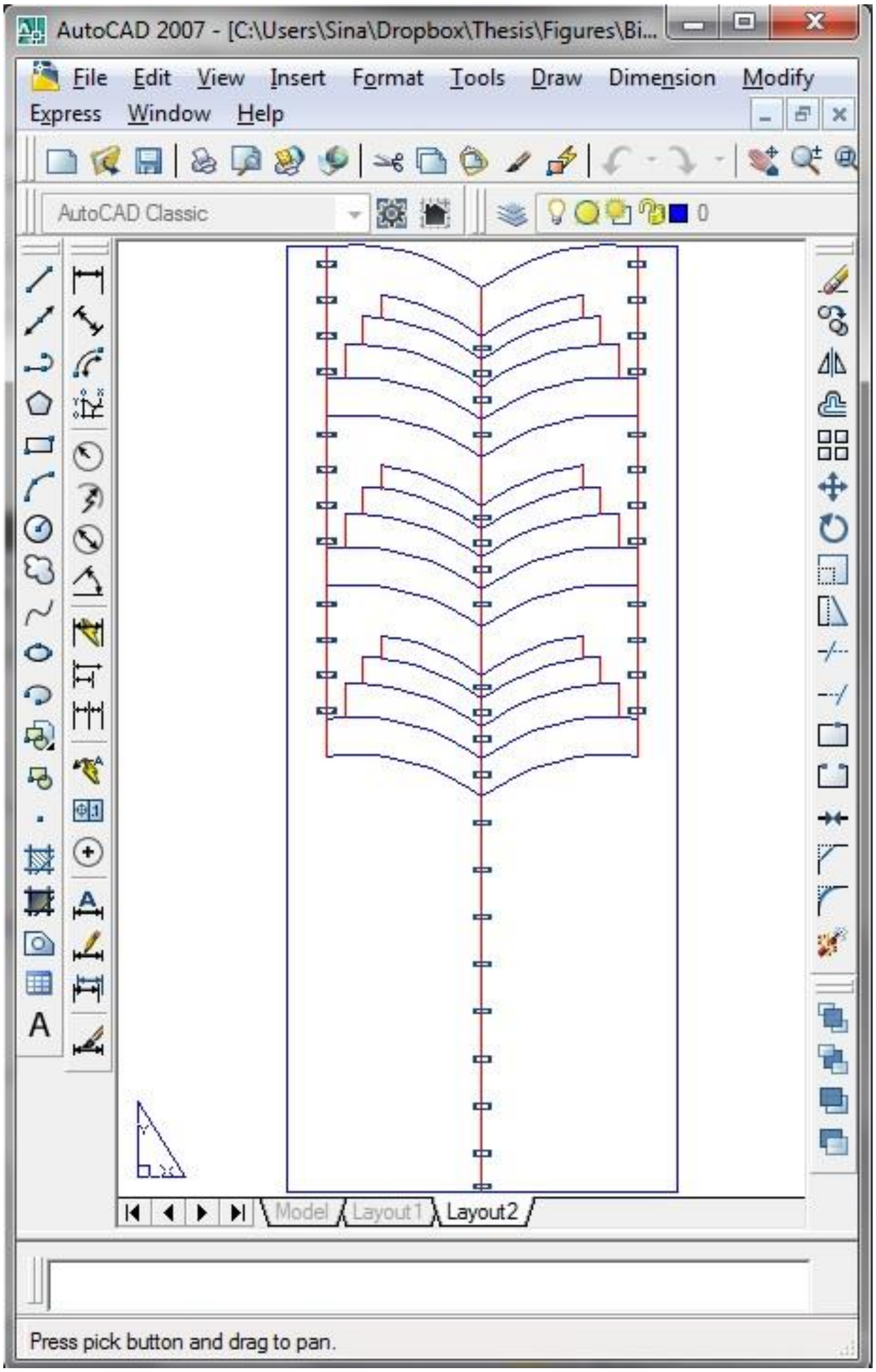


Figure 5.15: AutoCAD drawing of a lampshade including cutting/creasing lines and the location of polystyrene pieces.

Figure 5.16: Folded lampshade of Figure 5.15 lit with a light bulb on the inside.

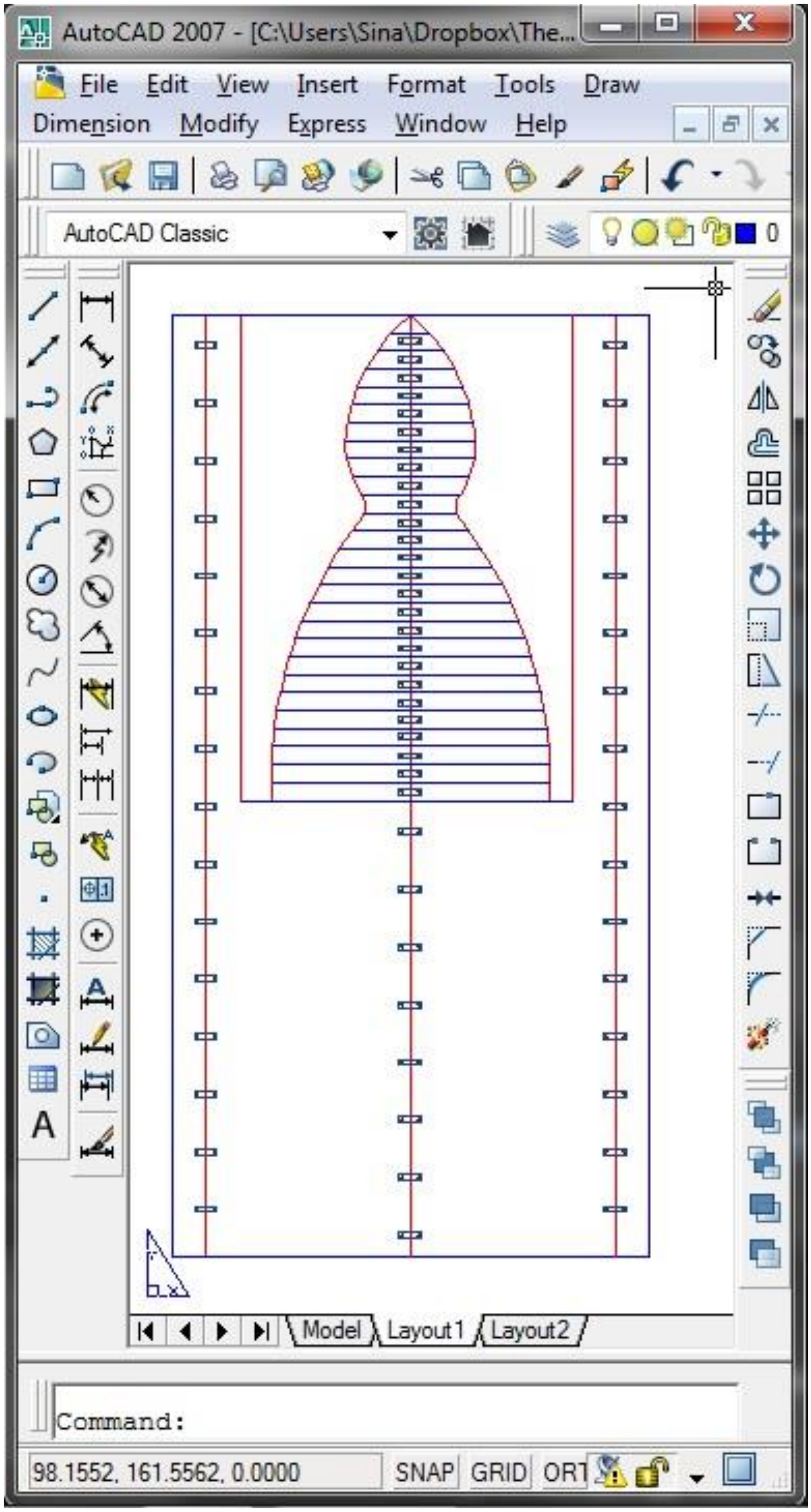


Figure 5.17: AutoCAD drawing of a lampshade including cutting/creasing lines and the location of polystyrene pieces.

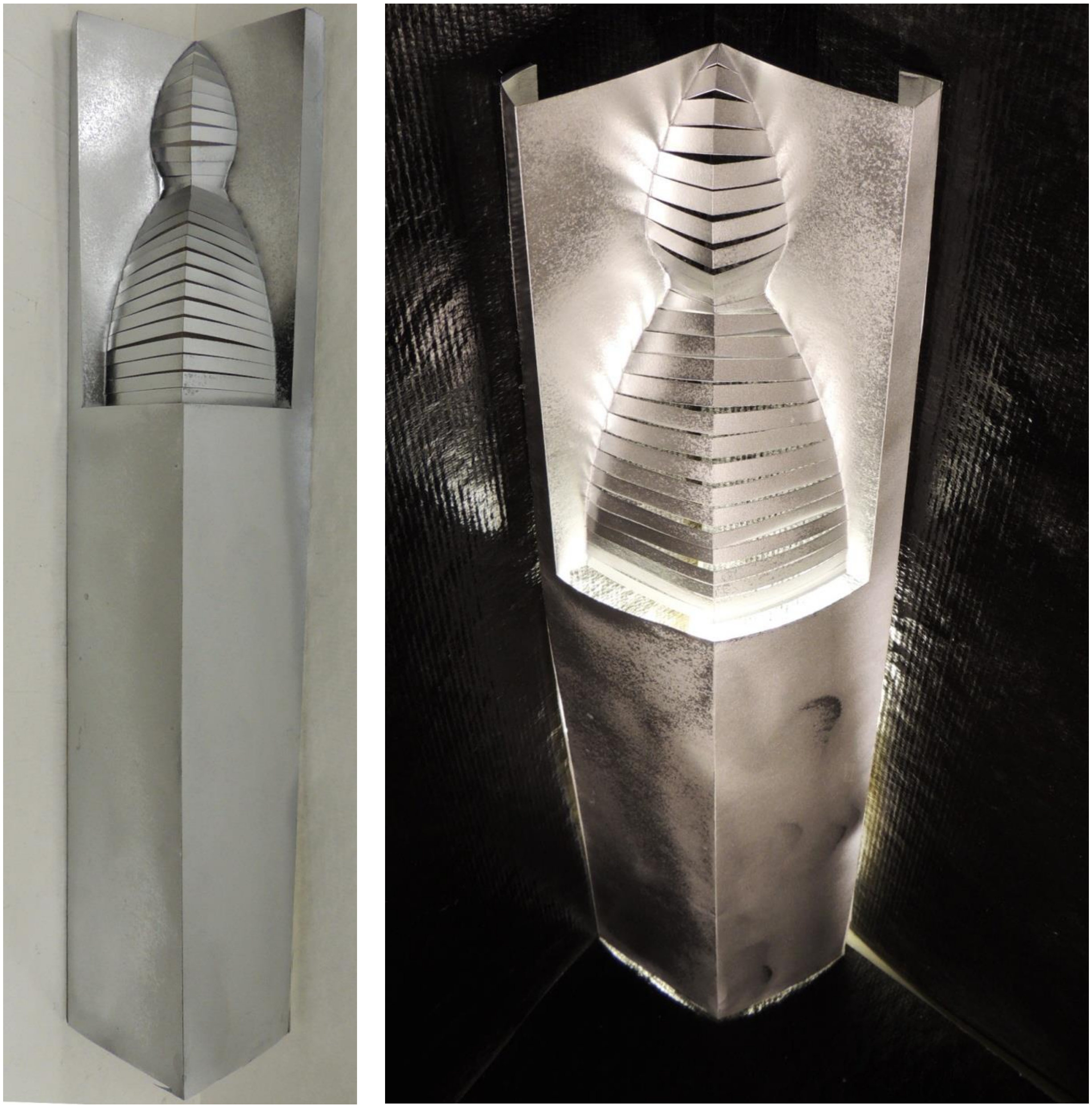


Figure 5.18: Folded lampshade of Figure 5.17 lit by a light bulb on the inside.

Figure 5.19: Folded lampshade lit with a light bulb on the inside.

5.4 Tessellation

More complicated models can be made and folded using the shrinkage polymer (the video is available on $YouTube^1$):

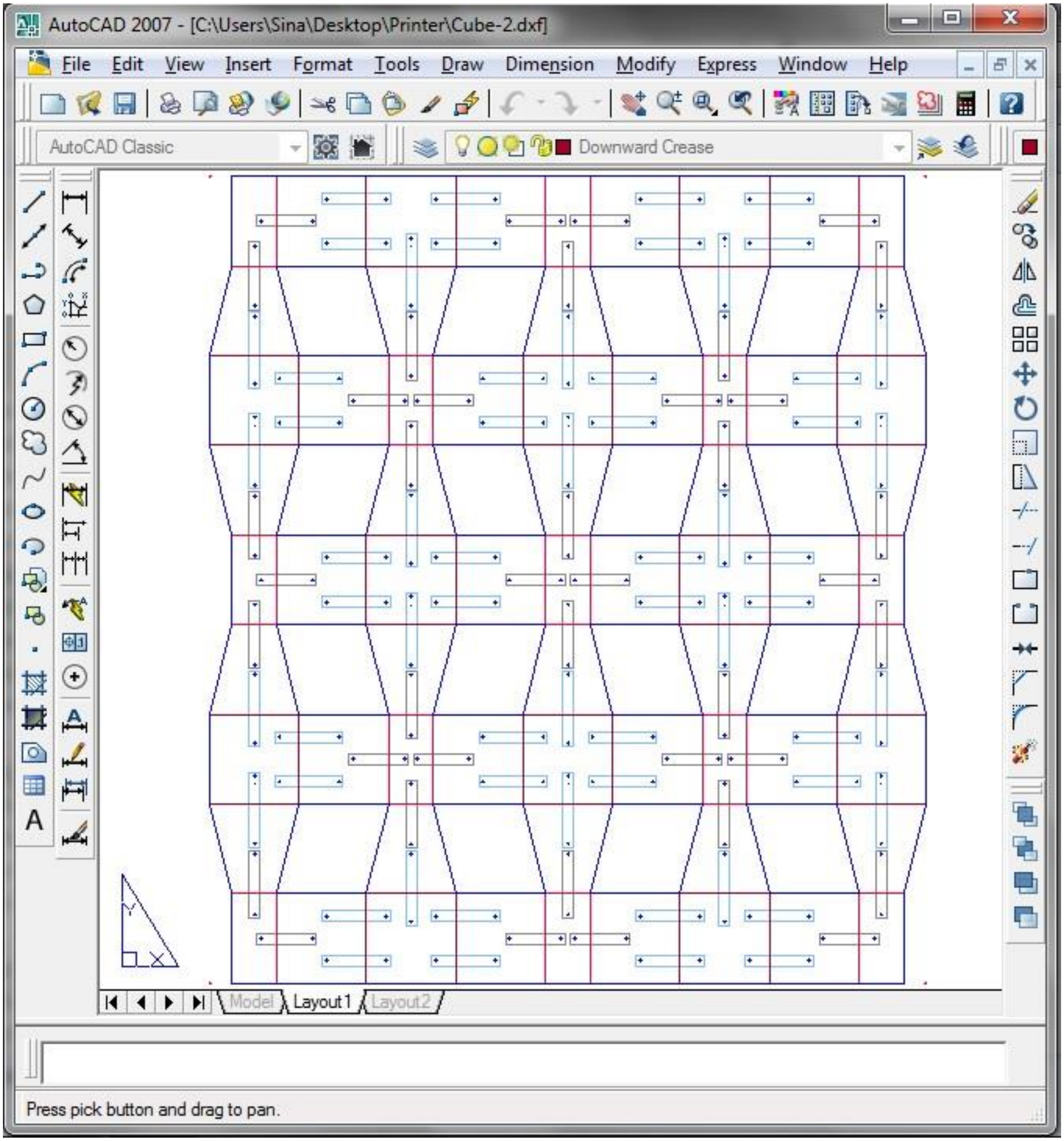
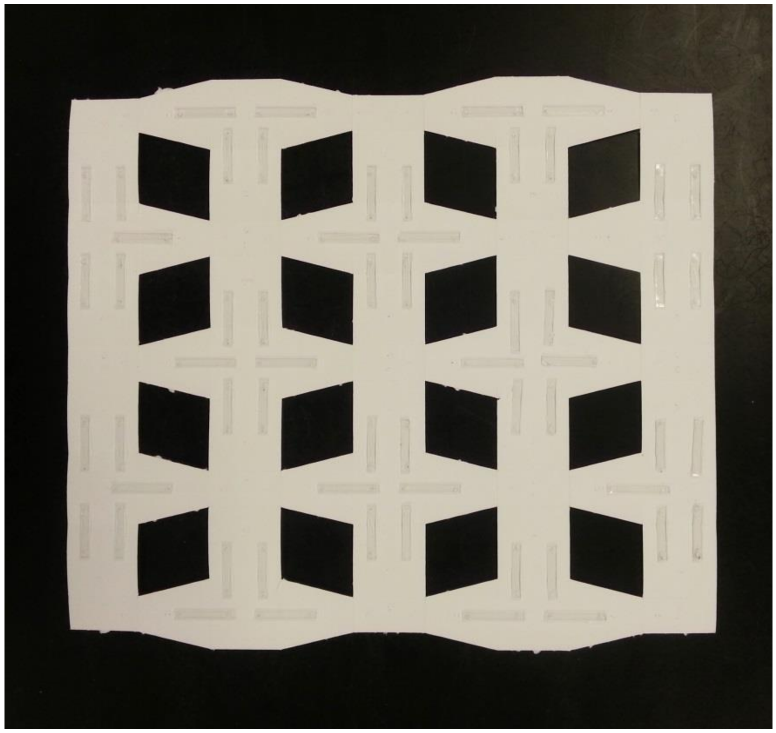
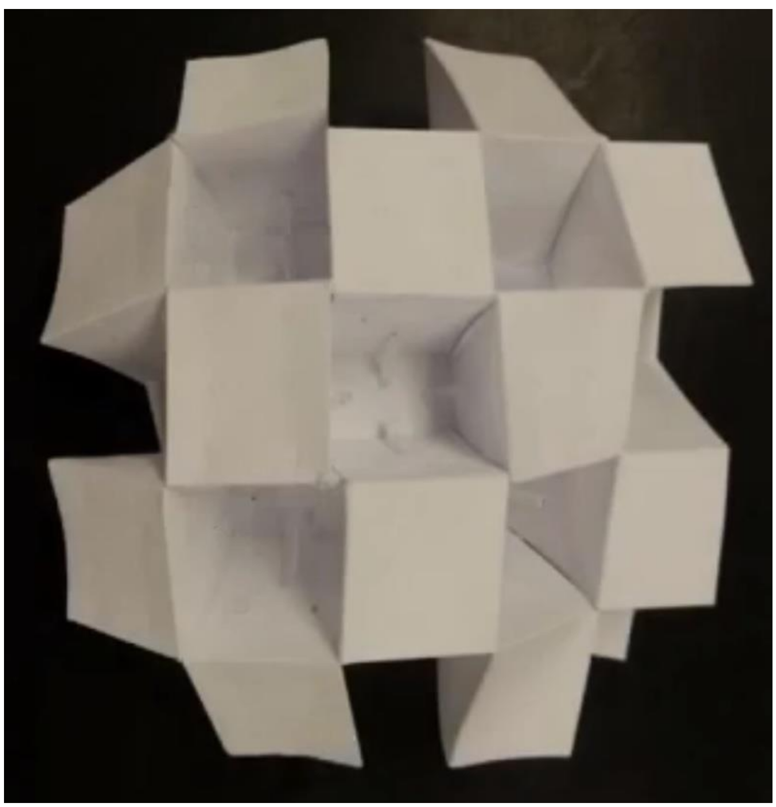


Figure 5.20: AutoCAD drawing of a tessellation model including cutting/creasing lines and the location of polystyrene pieces.

1 URL to "Pulp and Paper Centre, UBC, Cube" https://www.youtube.com/watch?v=6YG9oyDIIUs



(a)



(b)

Figure 5.21: Unfolded (a) and folded (b) tessellation model.

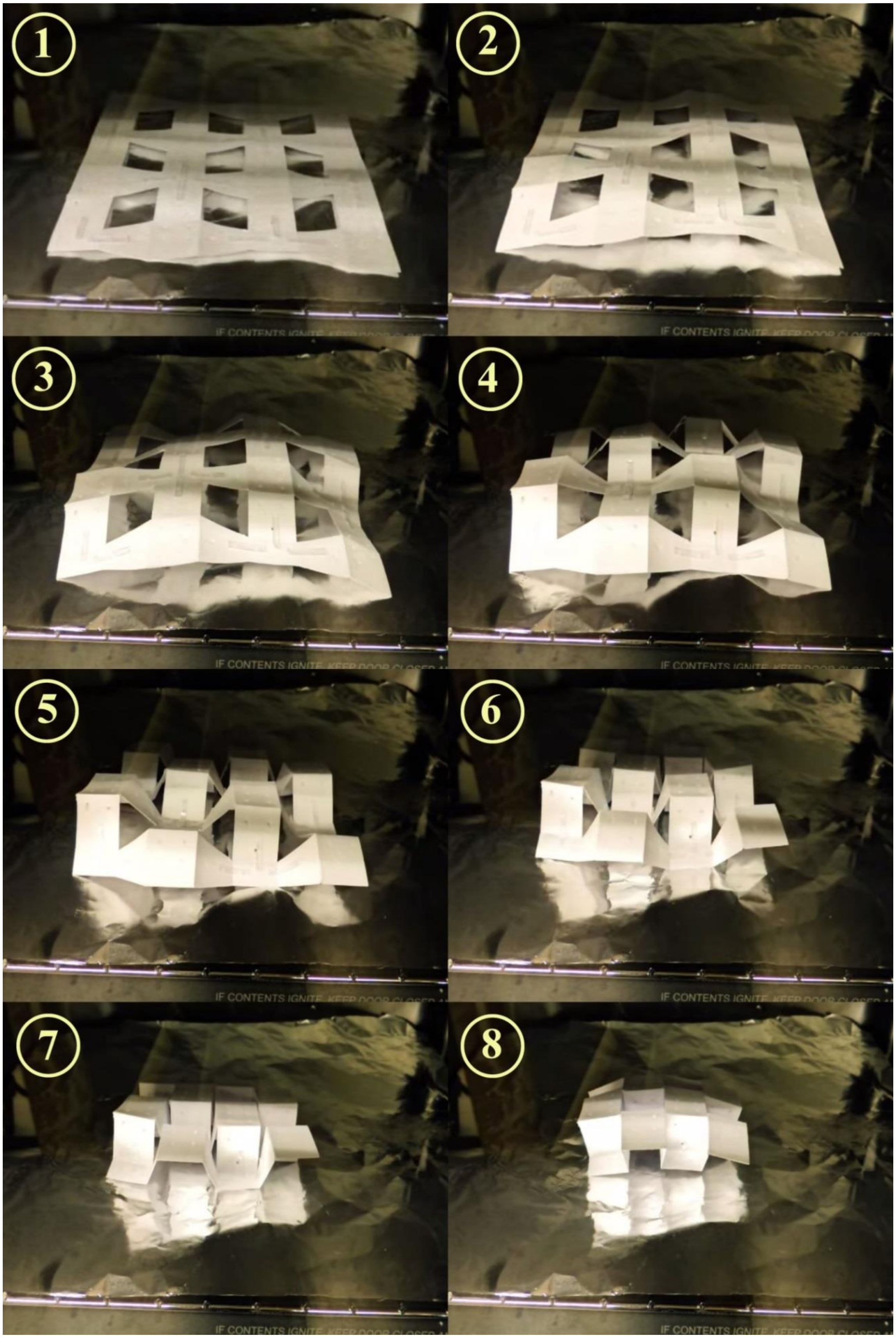
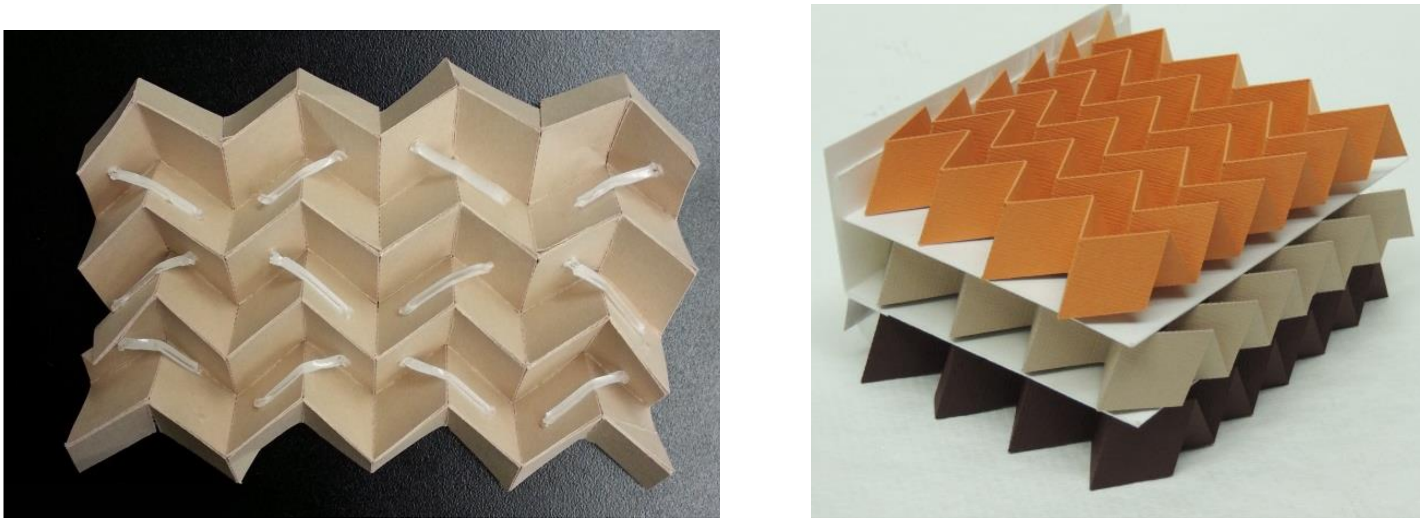


Figure 5.22: Tessellation folding process in eight frames.

There are also patterns with a strong final structure that can be used for heavy duty applications such as packaging or insulation. Figure 5.24 shows a small paper structure folded using polystyrene and can resist a weight of 10 kg. A series of this structure placed one over another can form a strong, usable device such as a bed or a chair.



(a) (b)

Figure 5.23: Folded tessellation (a) and a series of folded models placed on top of each other.

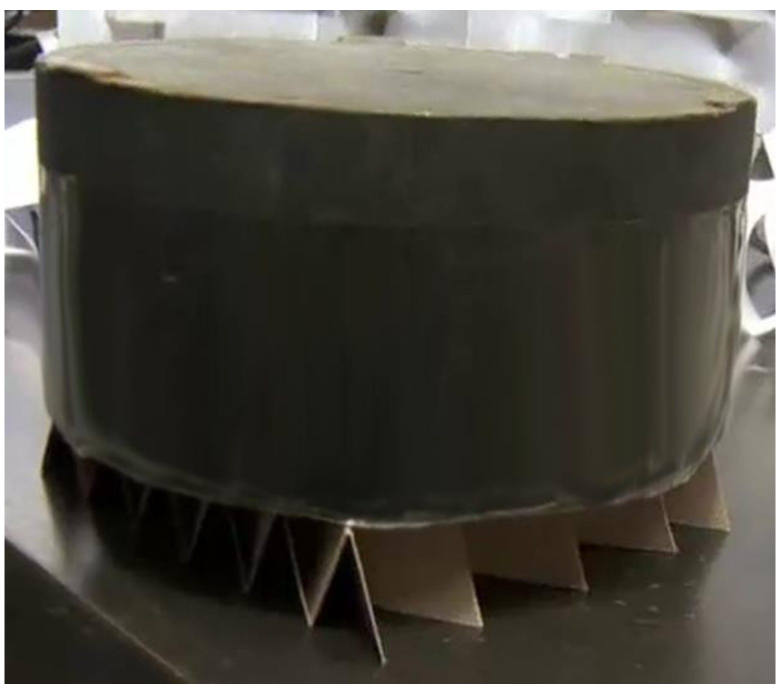
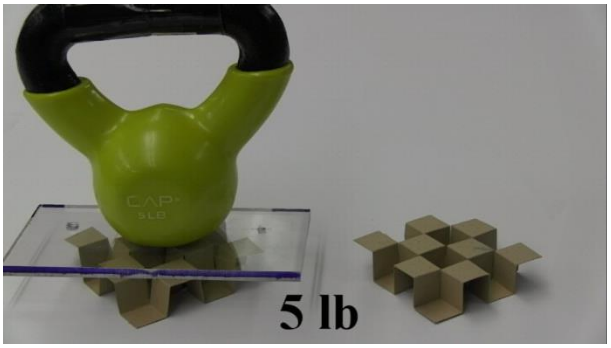
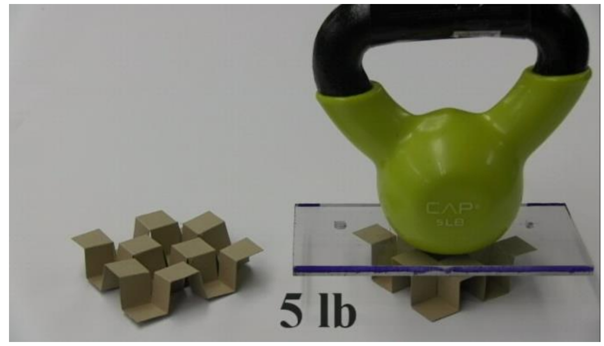


Figure 5.24: High strength paper structure resists a weight of 10 kg.

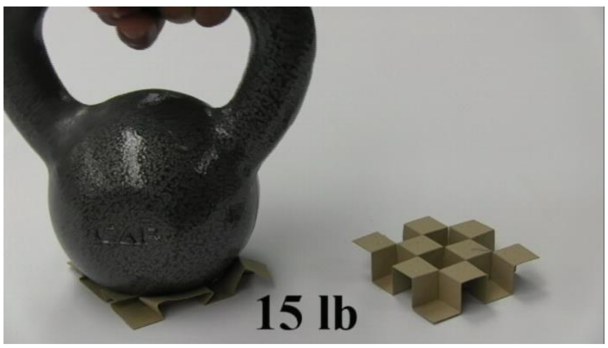
Similar origami models are strong due to the origami’s geometry, and the folding technique further increased the strength of the structure. The pieces of polymers that are added in the body of paper can act as an additional support for the structure. The effect of this method in the strength of the structure is examined and compared (Figure 5.25).



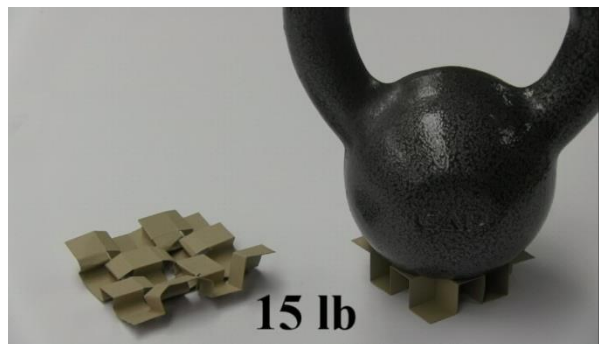
(a)



(b)



(c)



(d)

Figure 5.25: The left model is folded by hand without the addition of polymers, and the right model is made by machine and folded using the polymers.

Both models (a) and (b) can withstand the weight of 5 lb while the model which is folded by hand collapses under the weight of 15 lb (c) and the one is folded automatically can withstand it (d).
A larger size of model in Figure 5.25 can be used for different applications. It can be used to make acoustic layers and sound proof any place. It also can be utilized by the packaging industry to make additional protective layers to guard fragile products inside their box.

In summary, this technique has a high potential of making strong and inexpensive paper products as a replacement for ecologically irresponsible plastic products.

Chapter 6 – Conclusion and Recommendation for Future Work

This research developed a fully automated prototype that provides the potential to modify the methods to produce paper products. A unique technique was employed to create self-folding paper which led us to produce a range of 3D structure paper products (Chapter 6). The invented method facilitates making complicated origami models which is useful not only to produce various functional ultra-lightweight and incredibly strong paper structures, but also as a strong tool to simulate large self-assembling industrial structure using lower energy and less waste production.
This technique maintains the potential to use paper as a sustainable replacement for non-degradable material such as plastics. Developing this technique to industrial application conclude a significant decrease in fabrication process energy and ecologically irresponsible material.

Also in the procedure of making self-folding paper a new method created to connect polystyrene pieces to paper. Heat welding procedure was quite successful and it showed to be promising technique to make a strong polymer-paper bond. A series of experiments were conducted to determine the effect of pressure, temperature, welding attachment area and, thickness of paper on the paper-polymer bond strength and results showed that heat welding method can provide strong paper-polymer bond to fold paper with different thicknesses.

Another series of experiments was conducted to simulate paper folding angle. The general results showed that there is not a definitive correlation between folding angel and distance between polymer attachment points, though lower distance between polymer attachment points results in a wider folded angle, meaning the polymer shrinks less. This may be due to a nonlinearity of the shrinking at short lengths or the change in force exerted by the weight of paper on the polymer connection. Also in complicated models, while all the polymers shrink some internal forces are produced and it affects the polymer shrinking. As such, a separate simulation is recommended for different models.

The effect of increased paper weight (grams per square meter) increases bond strength. The reason is not clear because paper weight affects a large number of other paper properties, such as, thickness, density, surface strength of paper. This suggests that tests will need to be done for each paper weight used. We have also shown and quantified that folding angle is affected by:
-Paper thickness
-Paper density
-Polystyrene thickness
-Attachment strength
-Attachment distance
-Temperature uniformity
-The model geometry

The work in this thesis represents the possibility of folding the paper automatically to make 3D structures for different applications. The following recommendations provide possible studies that would facilitate the procedure of folding:

- Identify or manufacture thermoplastic polymer with different shrinkage ratio to make more complicated paper structures.
- Develop a fully automated prototype in order to make products in large quantities.
- Study stability and strength of different Origami structures.

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Appendix A-Inverse Kinematics Theory

In order to understand how the code works, one must comprehend how the inverse kinematics calculation works. The inverse kinematics calculation uses the desired x-y coordinates as inputs and outputs the angles of each motor. For a 2-degree of freedom problem, two motors to give simple unique solutions. The third joint for the z-axis control and pressure control is considered as a rigid joint with a known constant distance when aligned with the other joint and the tool touching the ground (paper) surface. In the explanation and analysis, the base pivot joint is reference to as the shoulder pivot and the middle pivot is referred to as the elbow pivot.

First we get the distance of the end effector from the shoulder pivot.

$$\mathrm{r} = \sqrt{(\mathrm{y}-\mathrm{b})^2 + (\mathrm{x}-\mathrm{a})^2}$$

Using Pythagoras and trigonometrics, we can easily solve for angle 1.

$$\mathrm{Ang1} = \arctan\left(\frac{\mathrm{y}-\mathrm{b}}{\mathrm{x}-\mathrm{a}}\right)$$

Using cosine law we can solve for the angle between the two links which is also the output angle for the elbow pivot. The zero angle for the elbow pivot is referenced by the elbow link pointing straight towards the shoulder pivot.

$$\phi = \cos^{-1}((\mathrm{L_1}^2 + \mathrm{L_2}^2 - \mathrm{r}^2)/(2\mathrm{L_1}\mathrm{L_2}))$$

$$\text{Elbow (rad)} = \cos^{-1}((\mathrm{L_1}^2 + \mathrm{L_2}^2 - \mathrm{r}^2)/(2\mathrm{L_1}\mathrm{L_2}))$$

Using sine law we can solve for angle 2 as shown:

$$\sin(\mathrm{Ang2})/\mathrm{L_2} = \sin(\phi)/\mathrm{r}$$

$$\mathrm{Ang2} = \sin^{-1}(\mathrm{L_2}\sin(\phi)/\mathrm{r})$$

Another solution can be derived using cosine law:

$$\mathrm{Ang2} = \cos^{-1}((\mathrm{L_1}^2 - \mathrm{L_2}^2 + \mathrm{r}^2)/(2\mathrm{L_1}\mathrm{r}))$$

The total shoulder pivot output angle is derived below:

$$\mathrm{Shoulder(rad)} = \mathrm{Ang1} + \mathrm{Ang2}$$

$$\text{Shoulder (rad)} = \arctan\left(\frac{\mathrm{y}-\mathrm{b}}{\mathrm{x}-\mathrm{a}}\right) + \sin^{-1}(\mathrm{L_2}\sin(\phi)/\mathrm{r})$$

$$\text{Shoulder (rad)} = \arctan\left(\frac{\mathrm{y}-\mathrm{b}}{\mathrm{x}-\mathrm{a}}\right) + \sin^{-1}(\mathrm{L_2}\sin(\text{Elbow (rad)} + \pi/6)/\mathrm{r})$$

This measured values can be used as the initial guess input.

$$\mathrm{a} \sim -15.59 \quad \mathrm{b} \sim 11.26 \quad \mathrm{L1} \sim 17.75 \quad \mathrm{L2} \sim 17.8$$

Appendix B-Calculation for the Amplification of Error

For Hitec Servo Motors

$$\text{Total Position Error (cm)} = \text{Servo 1 Error} + \text{Servo 2 Error}$$

$$\text{Total Error} = \text{R}\theta = (\text{L1} + \text{L2}) * \left(\pm 1° * \frac{\pi}{180}\right) + (\text{L2}) * \left(\pm 1° * \frac{\pi}{180}\right)$$

$$\text{Total Error} = 0.93 \text{ cm}$$

For Robotis Robotic Actuators

$$\text{Total Error} = \text{R}\theta = (\text{L1} + \text{L2}) * \left(\pm 0.08° * \frac{\pi}{180}\right) + (\text{L2}) * \left(\pm 0.08° * \frac{\pi}{180}\right)$$

$$\text{Total Error} = 0.074 \text{ cm}$$

Additionally, the motors were Arduino compatible and a library and microcontroller is available for interfacing specifically with these motors. Tutorials were posted on YouTube, and a forum on Trossen Robotics was available to consult.

Appendix C-Arduino Code

```
//Include the AX-12 Motor libraries
#include <ax12.h>
#include <BioloidController.h>

//Define the object bioloid Motor at its baud rate
BioloidController bioloid = BioloidController(1000000);

//Define Global Variables (Can be used anywhere in the program)
//Wrist_goal -Goal Position of wrist
float wrist_Goal;

//Define the wrist mapped angle val top val and bottom val
int up=640, down=535;

/* shldr_GoalMap/elbow_GoalMap - Goal Position
(angle of the shldr and elbow) */
int shldr_GoalMap, elbow_GoalMap;

//Used if needed to construct 2 byte parameters
int high, low;

//Present mapped angle vals of all the motors
int presentelb, presentshldr, presentwrist;
int wristread;

//Define channels used to tell apart the incoming data
char shldrChannel=1, elbowChannel=0, serialChar=0;

//Nov 7 feedback results with wrist=510 wristval sent still 505
//Compare the accuracy for 508, 509, 510
//Dec 4 change to 490

void setup() {
  Serial.begin(38400); // opens serial port, sets data rate to 38400 bps

  //Get a response from the motors
  Serial.println("Checking Motor Connection...");

  Serial.print("Shoulder ID: ");
  Serial.print(ax12GetRegister(1, 3, 1)); Serial.print("\t");
  Serial.print("Elbow ID: ");
  Serial.print(ax12GetRegister(2, 3, 1)); Serial.print("\t");
  Serial.print("Wrist ID: ");
  Serial.println(ax12GetRegister(3, 3, 1));
```

```
  Serial.print("Current Wrist Down value: ");
  Serial.println(down); delay(75);

  /*Set Arm Goal vals to an initial starting position
  the shoulder goes to 180 degrees (halfway point)
  the elbow goes to 60 degrees right angle to the shoulder
  elbow 60deg =205 */

  elbow_GoalMap = 205;
  shldr_GoalMap = 2048;

  wrist_move(up);                    //Move the wrist up initially

  sweep();                           //Move to initial position set above

  //Print the feedback table
  Serial.print("Shldr/Elbow Goal "); Serial.print("\t");
  Serial.print("Wrist actual "); Serial.print("\t");
  Serial.println("Present deg pos/mapped pos");
}
void loop() {

   while(Serial.available() <=0); //Wait for a character on the serial port
    serialChar=Serial.read(); //Copy the character from the serial port to the variable

    //Check to see if the initial serial character is the ID for the shldr channel ( should equal 1)
  if(serialChar == shldrChannel)
   { while(Serial.available() < 2);                    //Wait for two bytes from the serial port.
      shldr_GoalMap = Serial.read();   delay(10); //Assign the first byte to the low of the shoulder
goal
      shldr_GoalMap+= Serial.read()*256;              //Assign the second byte to the high of the
shoulder goal
    }

   while(Serial.available() <=0);                      //Wait for a character on the serial port
    serialChar=Serial.read();                   //Copy the character from the serial port to the
variable

  if(serialChar== elbowChannel)
//Check to see if the initial serial character is the ID for the elbow channel (should equal 0)
  { while(Serial.available() < 2);                     //Wait for two bytes from the serial port.
      elbow_GoalMap= Serial.read();    delay(10); // Assign the first byte to the low of the elbow
goal
      elbow_GoalMap+= Serial.read()*256;   //Assign the second byte to the high of the elbow goal
  }

    delay(100);
```

```
   sweep();                                   //Sweep to the goal values read from the serial

   wrist_move(down); delay(900);
 //Move the wrist down to the mapped angle value "down" and delay for 900ms

   wristread = ax12GetRegister(3, 36, 2); delay(100);
//Read the current position from the wrist and delay for 100ms

   feedback();                     //Get feedback from the shoulder and elbow

   wrist_move(up);     //Move the wrist up

   printresults();           //Send the feedback results and wrist down (actual) position to the
computer
}

/*Purpose:
 Move the shoulder and elbow motors to the goal position with a sequence of small fast steps
(sweep) */

void sweep(){


  feedback();               //Get the present position of the shoulder and elbow motors

  //Define the current pos of the elbow and shoulder as a local variable (only can be used in the
sweep function)
  int elb_pos;
  int shldr_pos;

  //Recheck the shoulder and elbow position if the values are below 0 (Safety from garbage values
or disconnection)
  if(presentshldr >=0) shldr_pos=presentshldr;
  else{  delay(100);
  feedback();
  }
  if(presentelb >=0) elb_pos=presentelb;
  else{  delay(100);
  feedback();
  }

  //Check if you need to sweep forward or backward
  if(elbow_GoalMap > elb_pos) //Condition for sweeping forward
  {  for(elb_pos = presentelb; elb_pos < elbow_GoalMap; elb_pos += 1)
   // goes from present pos to goal position in steps
    { SetPosition(2, elb_pos);     // in steps of 0.3 degrees tell the servo to go to position in variable
'pos'
      delay(10);                          // waits 10ms for the servo to reach the position
```

```
    }
  }
 else if(elbow_GoalMap < elb_pos)   //Condition for sweeping backward
  {  for(elb_pos= presentelb; elb_pos > elbow_GoalMap; elb_pos-= 1) //Goes from present pos to
goal position in steps
    { SetPosition(2, elb_pos);  //in steps of 0.3 degrees tell the servo to go to position 'elb_pos'
      delay(10);               //wait 10ms for the servo to reach the position
    }
  }

  SetPosition(2, elbow_GoalMap);  //Set the elbow to the goal position (to adjust/make sure it
reached the goal)

  //Check if you need to sweep forward or backward
    if(shldr_GoalMap > shldr_pos) //Condition for sweeping forward
  {  for(shldr_pos = presentshldr; shldr_pos < shldr_GoalMap; shldr_pos += 2)  // Goes from
present pos to goal position in steps
    { SetPosition(1, shldr_pos);      // in steps of 0.16 degrees tell the servo to go to position in
variable 'pos'
      delay(10);                    // waits 10ms for the servo to reach the position
    }
  }
 else if(shldr_GoalMap < shldr_pos) //Condition for sweeping backward
  {  for(shldr_pos = presentshldr; shldr_pos > shldr_GoalMap; shldr_pos-= 2) //Goes from present
pos to goal position in steps
    { SetPosition(1, shldr_pos);    // in steps of 0.16 degrees tell the servo to go to position in
variable 'pos'
      delay(10);                  //wait 10ms for the servo to reach the position
    }
  }
  SetPosition(1, shldr_GoalMap);  delay(200); //Set the shoulder to the goal position (to
adjust/make sure it reached the goal)
}

/* Purpose:
Move the wrist to wrist_Goal in a series of steps to slow the motor
*/

void wrist_move(float wrist_Goal){
  int wrist_pos;  //Define a local variable wrist pos for the present position

  presentwrist = ax12GetRegister(3, 36, 2); //Read the present wrist position

  //Recheck the wrist position if the values are below 0 (Safety from garbage values or
disconnection)
  if(presentwrist > 0) wrist_pos = presentwrist;
  else presentwrist = ax12GetRegister(3, 36, 2);
```

```
  if(presentwrist > 0) wrist_pos = presentwrist;
  else presentwrist=520;

  if(wrist_Goal > wrist_pos) //Condition for sweeping up
{  for(wrist_pos = presentwrist; wrist_pos < wrist_Goal; wrist_pos += 1)  //Goes from present pos
to goal position in steps
     { SetPosition(3, wrist_pos);       //in steps of 0.3 degrees tell the servo to go to position
'wrist_pos'
       delay(8);                     // waits 8ms for the servo to reach the position
     }
}
  else if(wrist_Goal < wrist_pos) //Condition for sweeping down
{  for(wrist_pos = presentwrist; wrist_pos > wrist_Goal; wrist_pos -= 1)  //Goes from present pos
to goal position in steps
     {
       SetPosition(3, wrist_pos);      //in steps of 0.3 degrees tell the servo to go to position
'wrist_pos'
       delay(8);                    // waits 8ms for the servo to reach the position
     }
}
  SetPosition(3, wrist_Goal);        //Set the wrist to the goal position (to adjust/make sure it reached
the goal)
  presentwrist=wrist_Goal; delay(100); //necessary delay
}

void feedback(){
  /*Reading a packet of length 2 from 36 is the same as combining a high byte
  from 37 and a low byte from 36 */
  presentshldr = ax12GetRegister(1, 36, 2);   //Read the present shoulder position
  presentelb = ax12GetRegister(2, 36, 2);    //Read the present elbow position
}

void printresults(){

  //Print the Values received from the serial and the present position of the motors
  Serial.print( shldr_GoalMap);   Serial.print("\t");
  Serial.print( elbow_GoalMap);   Serial.print("\t \t");
  Serial.print( wristread);    Serial.print("\t \t");

  //Map the present shoulder and elbow postion to angles print the result
  Serial.print( float (map(presentshldr, 1024, 3072, 0, 1800))/10 );
  Serial.print("\t \t");
  Serial.println(presentshldr);   Serial.print("\t \t \t \t \t");
   Serial.print( float (map(presentelb, 0, 512, 0, 1500))/10 );
  Serial.print("\t \t");
  Serial.println(presentelb);
}
```

Appendix D-Processing Code

```
import processing.serial.*;
/************Notes:
File wont read if there are extra lines with no data

**Nov 13/14 Updates:
Can input either coordinates or mapped angles from notepad
Indicate coordinates with "0 (tab) 1" in the first line
Indicate mapped angles with "1 (tab) 1" in the first line

**Nov 27 Update: Paper was wedged between the arm and wood to
reinforce it and prevent sagging.

**Nov 29 Update: Re-calibrated the feedback numbers at 516
Noticed the arm is unable to report the wrist value more due
to overworking perhaps. Noted it is very difficult to get to 505
now
Suggest raising the wrist down value
*/

Serial port;

// Nov 7 float humerus=(17.70), ulna=(17.52);
float humerus=17.615, ulna=17.62;
float xPosition;
float yPosition;
float x, y;

String []subtext;

char elbowvals[];
char shouldervals[];

ArrayList xydata;
ArrayList xcoords;
ArrayList ycoords;

ArrayList data;
ArrayList column1;
```

```
ArrayList column2;

//Define the elbow coodinates
float elb_x, elb_y;

//4.3 (0 to mid bracket) + 6.95
//last value a -15.3 b 11.11
//a= -15.2 +0.2 , b=11.26 +0.1
//Define the shifting coordinate system constants
//float  a=(-15.592), b=(11.24);
//Nov 7 float a=(-15.58), b=(11.30);
float a=-15.86, b=11.63;

//Define the length from the base to the end coords
float radius1;

//Define the angles in radians
float Ang1, Ang2;
float elbow_rad, shldr_rad;

//Define the solution angles in degrees
float elbow_deg, shldr_deg;
float shldr_Goal, shldr_GoalMap;
float elbow_Goal, elbow_GoalMap;

char shldrChannel=1;
char elbowChannel=0;

int high;
int low;

int timer;

void setup(){
  println(Serial.list()); // List COM-ports (Use this to figure out which port the Arduino is 
connected to)
  //port = new Serial(this, "COM9", 38400);
  port = new Serial(this, "COM11", 38400);
  port.bufferUntil('\n');
```

```
  data= new ArrayList();
  column1= new ArrayList();
  column2= new ArrayList();

  //readData("C:/xycoords2.txt");
  //readData("C:/xycoords3.txt");
  //readData("C:/xymap.txt");
  //readData("C:/Starpattern.txt");
  //readData("C:/Stairspattern.txt");
  //readData("C:/Nov7xymapFeedbackwrist-510.txt");
  //readData("C:/Nov14xymapFeedbackwrist-510.txt");
  //readData("C:/Nov29xymapFeedbackwrist-516.txt");
  //readData("C:/Nov30xymapFeedbackwrist-510.txt");
  readData("C:/Dec4xymapFeedbackwrist-535.txt");
  //Nov 30 all feedback results are not accurate

 if( (Float) column1.get(0)==0 && (Float) column2.get(0)==1){
  for(int j=1; j<data.size(); j++)
   {
     xPosition= (Float) column1.get(j);
     yPosition= (Float) column2.get(j);

     inverse_k(xPosition, yPosition);

     print(int (shldr_deg*10) + "\t");
     println(int (elbow_deg*10) + "\t" );

     shldr_Goal= shldr_deg*10;
     elbow_Goal= elbow_deg*10;

     shldr_GoalMap= map(shldr_Goal, 0, 1800, 1024, 3072);
     elbow_GoalMap= elbow_Goal*512/1500;

     high= int (shldr_GoalMap)/256;
     low = int (shldr_GoalMap) % 256;

     port.write(shldrChannel);
     port.write( low);     //Send the Elbow Position   (either type char or int)
     port.write( high);
    //Send the initial pan/tilt angles to the Arduino to set the device up to look straight forward.
```

```
     high= int (elbow_GoalMap)/256;
     low = int (elbow_GoalMap) % 256;

    port.write(elbowChannel);
    port.write(low);  //Send the Shoulder Position
    port.write(high);
    try
     {
      Thread.sleep(3000);
     }catch (InterruptedException ie)
     {
     System.out.println(ie.getMessage());
     }
   }
}
else if( (Float) column1.get(0)==1 && (Float) column2.get(0)==1){

  for(int j=1; j<data.size(); j++){
    shldr_GoalMap= (Float) column1.get(j);
    elbow_GoalMap= (Float) column2.get(j);

    print(int (shldr_GoalMap) + "\t");
    println(int (elbow_GoalMap) + "\t" );

    high= int (shldr_GoalMap)/256;
    low = int (shldr_GoalMap) % 256;

    port.write(shldrChannel);
    port.write( low);     //Send the Elbow Position   (either type char or int)
    port.write( high);
    //Send the initial pan/tilt angles to the Arduino to set the device up to look straight forward.

    high= int (elbow_GoalMap)/256;
    low = int (elbow_GoalMap) % 256;

    port.write(elbowChannel);
    port.write(low);  //Send the Shoulder Position
    port.write(high);

     try
     {
```

```
      Thread.sleep(3000);
     }catch (InterruptedException ie)
     {
     System.out.println(ie.getMessage());
     }
   }
  }

}

void inverse_k(float x, float y){

  //Calculate the length from the base to the end point
  radius1= sqrt((y-b)*(y-b) +(x-a)*(x-a));

  Ang1=atan2((y-b),(x-a));

  //Calculate the angle in the triangle between the humerus and radius
  Ang2=acos((humerus*humerus + radius1*radius1 - ulna*ulna)/(2*humerus*radius1));

  //Calculate the elbow angle using cosine law
  elbow_rad=acos((humerus*humerus -radius1*radius1 +ulna*ulna)/(2*humerus*ulna));

  //Convert angles into degrees
  //elbow_deg=180-degrees(elbow_rad);
  elbow_deg=degrees(elbow_rad)-30;
  //shldr_deg=180-degrees(Ang1)- degrees(Ang2);
  shldr_deg=degrees(Ang1) + degrees(Ang2);

  //Calculate where the elbow joint should be
  elb_x=humerus*cos(Ang1 +Ang2) + a;
  elb_y=humerus*sin(Ang1 +Ang2) + b;

}

/* The following function will read from a CSV or TXT file */
void readData(String myFileName){

  File file=new File(myFileName);
  BufferedReader br=null;
```

```
  try{
    br=new BufferedReader(new FileReader(file));
    String text=null;

    /* keep reading each line until you get to the end of the file */
    while((text=br.readLine())!=null){
      /* Spilt each line up into bits and pieces using a comma as a separator */
      subtext= splitTokens(text);

      column1.add(float(subtext[0]));
      column2.add(float(subtext[1]));
      data.add(text);
    }
      println(data.size());
  }catch(FileNotFoundException e){
    e.printStackTrace();
  }catch(IOException e){
    e.printStackTrace();
  }finally{
    try {
      if (br != null){
        br.close();
      }
    } catch (IOException e) {
      e.printStackTrace();
    }
  }
}
```

Appendix E-Automatic Cutting and Soldering Setup Manual

Introduction

This manual outlines the setup and operation of the CNC cutter/creaser for automating the creation of paper-polymer composite pieces ready to be placed in the oven for folding. For background on the folding process, see the Self-Folding Origami Product Project: Recommendation Report. The setup includes preparation of the CNC cutter hardware, inputting cutter driver settings to the cutter/plotter software, and drawing the pattern to be cut. There are processes and guidelines to be followed in each of the above steps to ensure proper operation and best results.

There is currently only one step in the operation that requires human intervention, but it is recommended for the user to supervise the operation of the machine when it runs so that the machine may be paused in the event of an error. An error may result in the destruction of the piece being created and damage to the cutter itself. While precautions to prevent errors and minimize the damage to the cutter from them are taken, it is still recommended that the operation be supervised, especially on the first run with a new piece.

Limitations

While this method allows the automatic attachment of polymer pieces to paper, creasing the paper, and cutting out patterns, it has a few limitations:

- Polymer can only be attached on one side of the paper. Double sided attachment can be achieved manually.
- Creases can be only done on one side of the paper. Perforating cuts can be done that allow folding along them but these cuts are not biased to fold in any particular direction.
- the size of the design is limited to the size of the polymer sheets. This can be overcome by careful placement of multiple polymer sheets.
- Intricate designs with fragile portions or a large number of holes have a higher chance of failure during the cutting stage.

Setup

There are several steps that must be done before operating the CNC cutter/creaser (a Graphtec Cutting Pro FC2250-180 with some modification to hold a Weller WES51 soldering iron). These steps include hardware and software setup as well as creating the pattern to cut.

While the below outlines the general setup, there are variables which would ideally be tuned before operating on different kinds of paper and different setups for best results. These variables are outlined in the "Variables" section of this manual.

Hardware

Hardware used in producing the paper-polymer composite is the CNC cutter/creaser and a soldering iron.

CNC Cutter/Creaser (Graphtec Cutting Pro FC2250-180)

Starting from a standard Graphtec Cutting Pro FC2250-180, the steps required to set it up for the production of paper-polymer composites are (1) adding the modification pieces to hold the soldering iron, (2) setting the machine side settings, (3) adding protective sheeting in the cutting area to prevent damage to the cutter surface in the event of an error, and (4) setting up the soldering iron.

Adding Modification Pieces

In order for the FC2250 to hold the soldering iron in place, a specialized holder head and jig are required. To mount the jig and holder head follow the next steps:

1. Move the head to an easily workable position by using the arrow keys on the cutter control panel and turn the machine off. It may speed the process to press the "Next" button while moving the head as this allows the cutter head to move much faster.
2. Remove the tool and tool holder on tool 1. The tool number is labeled on the tool head. Keep the screws from detaching the tool holder. See Figure 1.
3. Prepare the white tool holder made of heat resistant polymer by placing an M5 dome head screw through the clamping section and adding a nut. See Figure 1.
4. Affix the white tool holder made of heat resistant polymer to tool 1 using the screws taken from step 2.
5. Attach the two piece jig to the cutter head as shown in the Figure 1 below. Use a pair of needle nose pliers to hold the nut at the bottom while tightening the screws.
6. Counter tighten a threaded hook onto the topmost hole on the polycarbonate piece and attach a spring to the end of the hook. Choose a weak spring that is just enough to hold the soldering iron up when mounted. A strong spring will reduce the amount of force the soldering iron is capable of putting on the paper for polymer attachment, and potentially cause the machine to detect error (refer to “Debugging and Troubleshooting ").

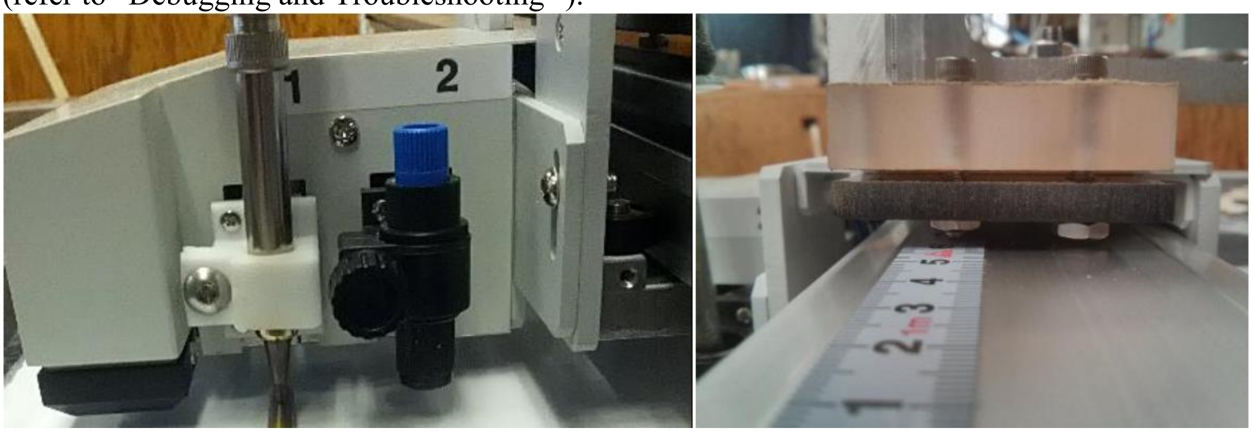

Figure E.1: Soldering iron tip holder mounted on cutter head (left) and two piece jig fixed with screws (right).

Machine Settings

The machine has multiple settings and conditions that can be set. For the creation of paper-polymer composites, only condition 4 and 8 will be used. The settings for each condition can be seen in Figure 2 below.

Figure E.2: Cutter side settings to be set on the cutter

The Offset and Force variables may need to be adjusted depending on the spring and how the holder is attached. See the Variables section for more details on how to change these and the effects they may have.

Protective Sheeting

To protect the area on which the cutter will work, it is recommended that protective sheeting be put in place. This sheeting also helps attach the polymer sheets to the cutting surface. The "Chart Hold" button can activate static electricity on the surface to hold paper in place, but this has little effect on the polymer.
1. Attach a smooth sheet of polymer to the cutting surface using tape.
2. Place a piece of printer paper over the polymer and tape it down using double sided tape. This double sided tape will double as a way to keep the sheet of polymer being worked on to the surface.

Soldering Iron

The soldering iron employed is a Weller WES51 soldering station and iron. If a different iron is used, a different holder will need to be made. The soldering iron must be set at the appropriate temperature and height, used with the appropriate soldering tip.
1. Make sure that the solder station temperature is set at 600F. (Tuning of this temperature may be required depending on the type of paper used for operation)
2. Set machine condition to tool2 so that the soldering iron holder is free to move up and down.
3. Mount a short soldering tip to the iron so that the holder will clamp around the cylindrical portion of the iron with the conical tip hanging below. See Figure 3 below for reference.
4. Slide the soldering iron into the holder on the tool head and hook the spring to the cable extending from the iron.
5. Calibrate the height of the soldering iron. Depending on the thickness of the paper to be used, the height of the iron will have to change. See "Soldering Iron Settings" for more details.

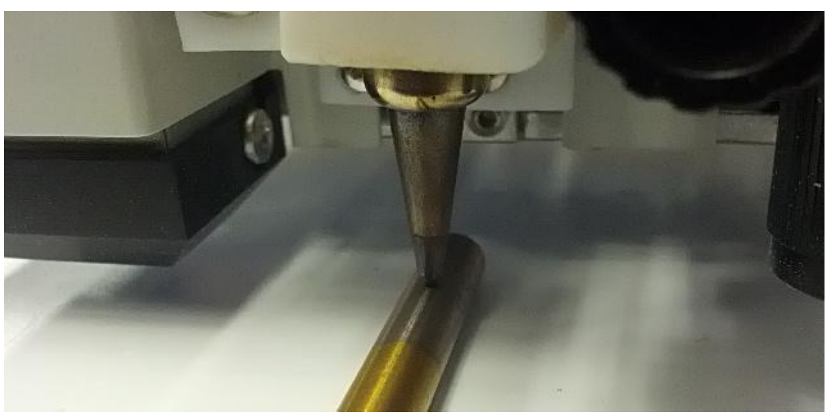

Figure E.3: Calibrating the soldering iron height using a drill bit.

Software

Two programs are essential to running the FC2250: Cutting Master 2 and one of CorelDraw or Adobe Illustrator. Although a standalone plotter program called Graphtec Studio can be installed as well, this manual will mainly focus on plotting with Adobe illustrator. After installation of

Cutting Master 2 and integrating the plugin, settings from the plotting must be specified for different operations (cutting, creasing, soldering).

Programs

Cutting Master 2 can be downloaded from the following link:
<http://www.graphtecamerica.com/graphtec-america-support-downloads-cutting-plotters-fc2250-series-flatbeds>
First install the appropriate plotter driver for your computer. Then install the Cutting Master plug-in for illustrator/CorelDraw. Once installed, this plug-in should be accessible from the drawing program.

Cut/Plot Settings

After installing the software, open the drawing program of choice and go to File->Cutting Master 2->Cut/Plot.... This will open a window that allows modification of cutting and plotting parameters.
Open the second tab and check the "Enable Driver Options" box. Input and save the settings listed in Table 1 below for future use.

Cutting/Plot Program Condition Setting				
Preset Name	polymercut	soldertool1	cardstock_crease_tool2	cardstock_cut_tool2
Condition	8	4	8	8
Force	60	40	15	28
Speed	40	1	40	40
Quality	6	6	6	6
Line type	1	1	1	1
Passes	3	6	1	1

Table E.1: Table of software side settings.

Drawing your design

The drawing of your design can be done in any software as long as it can export to a file format that either CorelDraw or Adobe Illustrator can read or import. There are merits and demerits to using different programs and it is best to choose your software depending on your needs. There are otherwise more general guidelines and operations that must be performed in the software from which you send the cut/plot commands.

Drawing Software

Besides using vector drawing programs such as Adobe Illustrator, CorelDraw, and Inkscape, one can use CAD programs such as SolidWorks and export as a DXF file. The merits to using a CAD program are:
● Geometrically accurate drawings.
● Easier to create symmetrical structures and specify dimensions in general.
Demerits include:
● Requires moving parts of the imported drawing to separate layers for different operations
● When in operation, shapes are not recognized as individual entities but as a collection of lines which may be cut in any particular order. This is particularly a problem with the cut patterns for polymer, as it cuts multiple times over each side of the shape separately instead of cutting the whole shape outline all together at once.

The ease of drawing using a CAD program usually far outweigh the demerits of having to do small modifications in the drawing program at the end.

Drawing Guidelines

Cutting Master 2 has a number of ways it can interpret the cut/plot design. The "By Layer" interpretation was used for the creation of the paper-polymer composites. In this mode, Cutting Master 2 allows specification of operational settings for each layer and ordering of operations in the order of layers listed. A few notes on this follow:

● Layers will be cut from the topmost layer to the bottommost.
● Items within each layer will be cut from topmost to bottommost. (Expand what is inside each layer using the layers window).
● Items in a group will be cut from topmost to bottommost
● Settings for each layer can be set in the window immediately before sending the cut/plot commands to the cutter. (See section, "Operation: Settings")
● Layers must be made visible to cut.

The four main types of distinct layers required are paper-cutting layer, paper-creasing layer, soldering-point layer, and polymer-cutting layer as can be seen in Figure 4.

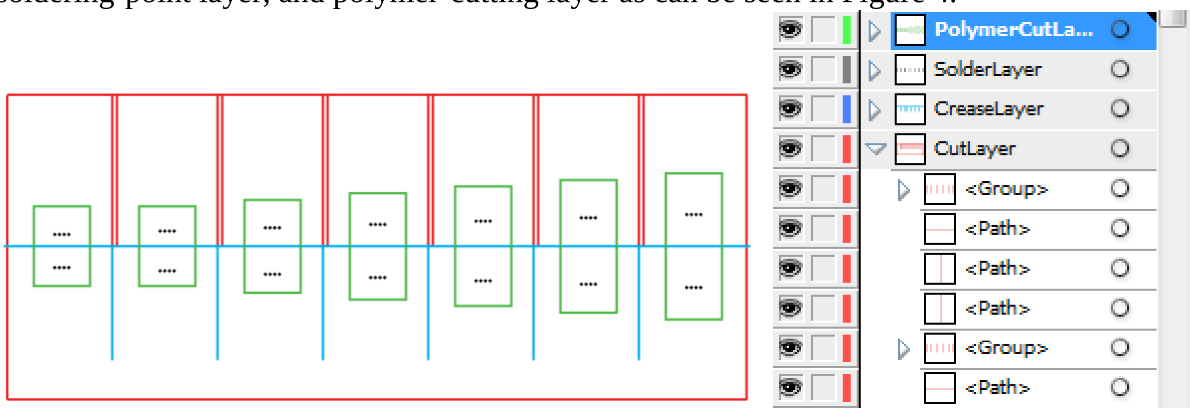

Figure E.4: A sample design of a paper-polymer composite test piece. The layers are color coded, polymer cut-green, soldering-black, paper creasing-blue, paper cutting-red. The layers will be cut from top to bottom (right).

1. Paper-cutting layer - This layer defines the overall outline of the flat pattern design and cut lines to be made inside of it. Depending on the geometry of the cut lines, it may be necessary to order them in a particular order so that paper does not tear off in the middle of cutting. This problem usually arises with intersecting lines and small intricate designs.
2. Paper creasing layer - This layer defines the folding lines in the design in the form of crease lines. While similar precautions need to be made as the paper cutting layer, problems don’t usually occur in this part since the paper remains intact.
3. Solder point layer - This layer defines the soldering points between paper and polymer for attachment. The soldering operation is done by moving the soldering iron around on a very small circle such that it is essentially applying force to a single point.

● The solder points should be circles with a diameter of 0.6pt or more (approximately 0.21 mm).
● Solder points should be placed symmetrically across a fold line.
● Instead of single points, it is possible to place a row of solder points about the fold line in parallel. However, the distance between each point in a row must be sufficiently small (~ 2pt, or

0.7mm), so that shrinking of polymer between each point does not deform the paper along that direction.

● After placing the solder points in the appropriate locations, the solder points must be offset downwards by 2pts. This is due to the soldering iron tip not matching the location of the tool tip of the commercial tips.

4. Polymer cutting layer

- This layer defines the polymer shapes to be cut. Generally speaking, these are rectangular pieces. Each polymer piece will be attached across a crease line at the soldering points defined above, so that shrinking them upon heating will induce a fold about the lines.

● Design the polymer cut by first determining the distance between two symmetrically placed solder points across a fold line. Make the polymer piece twice as long as the distance measured, and place it along the two points, symmetrically about the fold line once again.

● Wider polymer cuts are generally better but this will be limited by the design.

Although the layers should be designed in the order listed above to properly define geometrical relations between the cut lines, crease lines, and soldering points, the actual machine operation will be performed in the reverse order as explained below.

Operation

There are four main stages during the operation of the cutter/creaser: cutting the polymer, attaching the polymer to the paper, creasing the paper, cutting the paper. Manual intervention is required just before the soldering stage, and then at the end just before the machine resets.

If an error occurs at any point in time during the operation, press "Pause" on the cutter control panel. If the cutter does not respond to a layer being sent, click "Cancel" and the job will be aborted.

Settings

The following steps must be performed immediately before sending the cut/plot commands to the cutter.

1. Place the polymer sheet on the cutting area, making sure that it is firmly attached to the double-sided tape below over the protective sheeting.
2. Turn on "Chart Hold" on the cutter.
3. Move the cutter head to the desired starting point using the arrow keys on the cutter control panel. The speed of movement can be changed by pressing the "Next" button on the control panel while moving.
4. Press the "Origin" key once in position to set the origin.
5. In your drawing program, select "File->Cutting Master 2->Cut/Plot..." from the dropdown menu.
6. Select the second tab from the left to go to the "By color/By layer" options
7. Select "By layer"
8. Check the "Pause between colors/layers" box
9. Check the "Enable driver settings" box
10. Select the appropriate setting (as outlined in "Setup: Software - Cut/Plot Settings") for the appropriate layer.
11. Press send

Upon pressing send, a dialogue box will come up asking to continue with the cutting for each layer, starting with the polymer cutting layer. Figure 5 below shows the dialogue boxes present during operation.

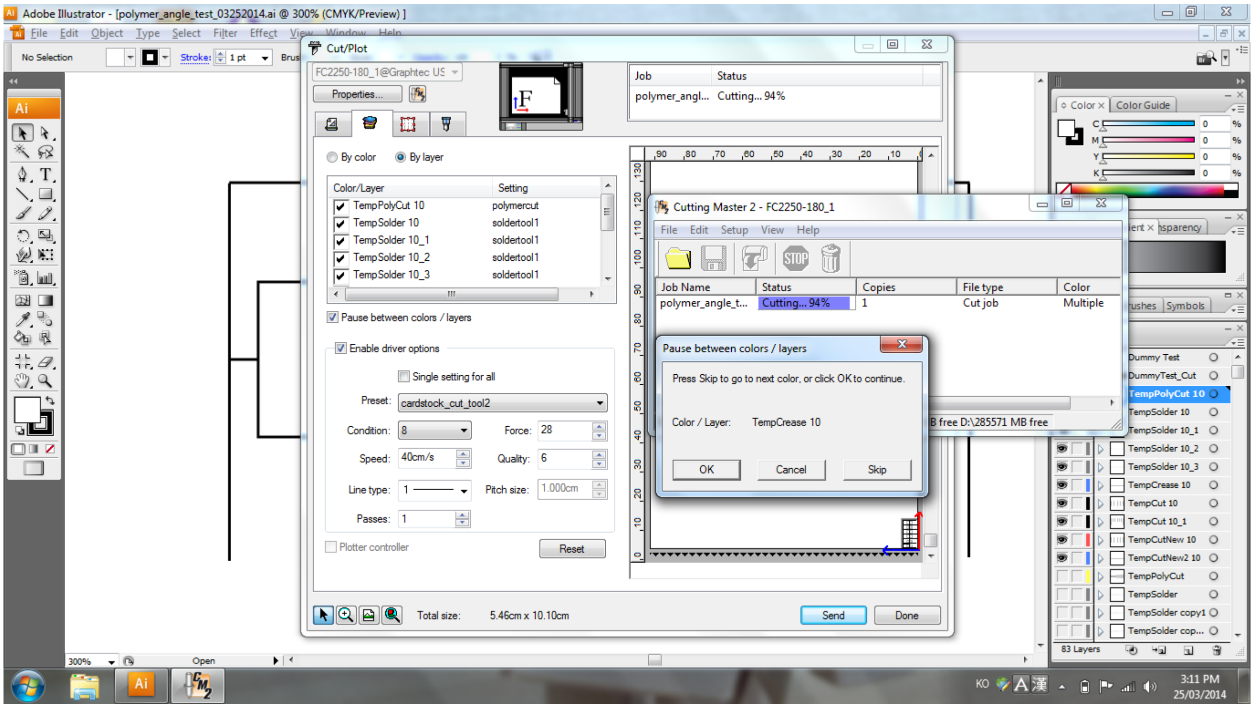

Figure E.5: The dialogue windows present during operation.

Polymer cutting

Clicking "OK" will start the polymer cutting process. A second dialogue box will pop up asking to start the soldering layer. Do NOT click "OK" yet. There is a manual step required in between cutting the polymer and soldering.

Watch to make sure that the polymer is being cut at the appropriate strength and that the polymer does not detach from the surface. In the event that the polymer does detach, press "Pause" on the cutter control panel, and press the Stop button in Cutting Master 2. If the polymer has moved significantly or the polymer has ripped, abort and delete the current task in Cutting Master 2, and press "Enter" and "Origin" button at the same time on the cutter control panel to reset the cutter. The print job will be abandoned and the cutter will reset.

Soldering

After the polymer has been cut successfully, slide the paper to be used between the polymer sheet and the tool head. Care will be needed to not dislodge the pieces of polymer that are cut and detached from the sheet. This may be easier to do by turning “Chart Hold” off temporarily.

Attach the paper to adhesive that is left over around the polymer sheet and to the table. Enabling "Chart Hold" will cause a buildup of static electricity on the surface of the cutter that will attract paper to the surface.

Once the paper is in place above the polymer, check to make sure the soldering station is on and set at the right temperature. Then, click "OK" in the dialogue box.

Paper creasing

Once the soldering is completed, detatch the soldering iron from the station and wrap the cable around the jig so that it does not interfere with the rest of the operation. For the same reasons, move the soldering station off of the cutting surface.
Click "OK" to the creasing layers.

Paper cutting

No further intervention is needed from the user. Press click "OK" to the rest of the layers (if the user specified multiple cutting layers) and observe the cutter. In event of an error, press "Pause" on the cutter control panel. Once the job is done, after a short delay, the cutter head will move to the far right top corner of the machine.
Afterwards, turn “Chart Hold” off and carefully detach the paper and polymer sheet together from the cutting surface. Then, push the polymer pieces out of the polymer sheet. After all polymer pieces are detached from the polymer sheet, the paper-polymer composite is now complete and ready to be put in the oven for folding. An example is shown in Figure 6 below.

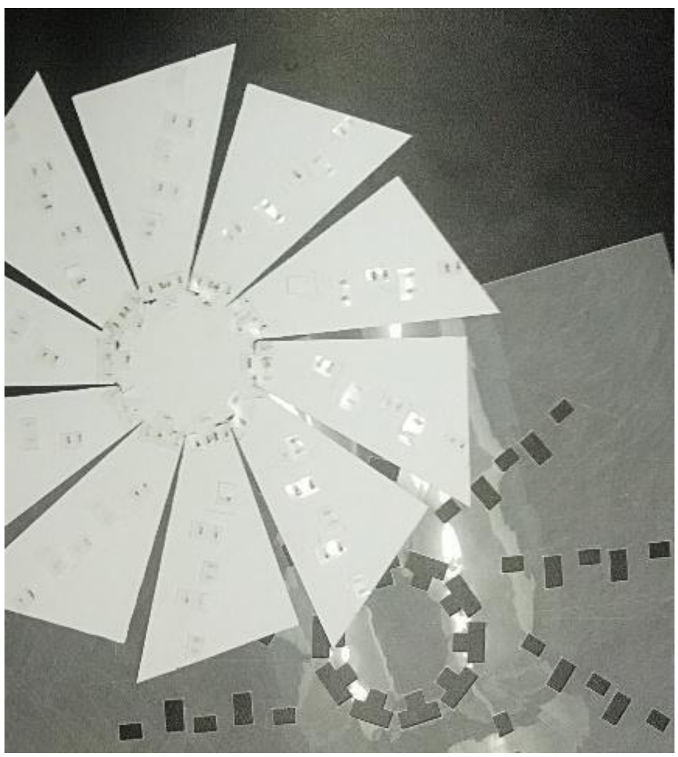

Figure E.6: Example of a paper-polymer composite detached from the polymer sheet.

Debugging and troubleshooting

Outlined below are common issues that may arise while operating the cutter, and techniques to deal with each.

Cutter is not responding to a job/layer being sent

Look at the cutter control panel. If "Online" is displayed, it means the cutter believes it is communicating with the computer and is busy. Cancel the current job, wait until "Ready" is displayed, and resend the job. If the cutter stopped communicating in the middle of a job, skip layers until you reach the point you were previously at and start sending from there.
Else, close the "Cut/Plot..." window, restart Cutting Master 2, and restart the cutter.

Cutter does not allow the origin to be set/Cutter keeps moving back to last origin

Try moving the cutter and setting the origin at a different location before moving to your target location.
If this occurs too many times the cutter will throw an error and you will need to restart the cutter.

Cutter beeping

Restart the cutter after identifying the cause of the error. Common causes include X,Y position stability, the soldering iron being too low, the spring resisting the vertical movement of soldering iron too strongly, and the cutter head running into obstacles.

Not enough force applied when soldering/cutting

There are two main causes for not enough force being applied. The first is inputting a value that is out of bounds in the "Force" field in the driver options. Tool 1 is only capable of up to 40 units of force and if a value greater than 40 is input in the field, no force will be applied. Similarly, Tool 2 is only capable of up to 80 units of force.
The second cause is an internal error that displays a force on the driver options but sends a different force to the cutter. To fix this error, close the "Cut/Plot..." window and restart Cutting Master 2.

Soldering iron is ripping the paper and melting through the polymer

This means either too much force is being applied, the soldering iron is too hot, or the iron is being applied for too long. Lower the iron temperature, apply less force by changing the value in the driver options or raising the height of the soldering iron, or decrease the number of passes the soldering iron does over its patterns (decrease the time).

Variables

Cutter Driver Options Settings

These are set and saved before cutting or can be adjusted immediately before cutting. They control the way in which the cutter will operate on the media. See the FC2250 User Manual for more details.

Condition

There exist conditions 1~8 which reflect the cutter settings on the cutter. The reason for changing these are only if the holder on which the tool is attached is changed. Conditions 1~4 use tool 1 and conditions 5~8 use tool 2 by default. This can be changed in the Cutter Settings.

Force

Force for tool 1 ranges between 1 and 40 units and 1 to 80 units for tool 2. One can determine the appropriate amount of force by setting the forces on the cutter control panel and making a test cut on the media. With a lighter force, the cutter is capable of making light cuts that act as creases.

Speed

The speed at which the cuts are done in cm/s. Maximum speed is 40cm/s and minimum is 1cm/s. Faster operation is generally desired. Slow operation is mandatory only for soldering when the soldering circles must be done slowly so that the iron takes time to stay in position.

Quality

Ranges from 1 to 6 ranging from worst quality to highest.

Line type

Sets the kind of cut the blade will do. Default is a solid line cut. Possible uses for different line types may be perforating cuts for a fold that could go either way.

Passes

The number of times a single cut is looped over. For thick media such as the polymer, this is number is greater than 1. The same applies to soldering layers so that the iron spends more time on the point by looping over a circle.

Cutter Machine Settings

These options are almost all overwritten by the Driver Option Settings during run time but it is good to set them the same as the Driver Option Settings in event of an error or needing a test case. Parameters Force, Speed, and Quality can be set for each condition in the same way as described above. By pressing "Test" on the control panel and selecting "Test 1", a test cut can be performed to see the effects of the settings. There is only one new parameter that can be set on the cutter, which is the offset.

Offset

A horizontal offset must be set so that both tooltips align when in operation. With no offset, the cuts of one tool may be offset from the other. This is important since the soldering iron is a custom made tool holder and tip it will require an offset to match the other tool.

Soldering Iron Settings

The soldering iron must be set in such a way that the heat and pressure it applies is enough to attach the polymer to the paper but not too strong that it goes through the protective layer and into the table.

Temperature

The dial on the solder station can be used to set the temperature of the soldering iron. Approximately 600F was found to be near optimal but this varies with the pressure applied, as well as the thickness and type of paper used.

Height

The height of the soldering iron in its holder changes the amount of pressure applied at the same force setting. If set too low, the cutter will throw an error. The lowest height that was found to work was 7/32 inches off the cutting surface while the tool was not being engaged by the machine. (This height was measured using standard drill bits, see Figure 3).

Spring constant

The spring holding the soldering iron up should be strong enough that it will hold the iron up when the iron's tool is not engaged but should not be too strong that it will reduce the force the iron applies to the paper.

Soldering iron tip

The soldering iron tip can be modified to have a smaller area which will cause a larger pressure.

Appendix F-Experimental Results for Heat Weld Strength Attachment on Hardwood Paper with Thickness of 0.1 mm.

Paper Thickness (mm)	Contact Diameter (mm)	Force (gf)	Temperature (°C)	Mean Failure Force (N)
0.1	1.2	500	90	6.4
			100	8.3
			110	10.0
		1000	90	7.3
			100	9.6
			110	11.2
		1500	90	7.9
			100	10.2
			110	11.6
		2000	90	8.5
			100	10.7
			110	12.0
	1.8	500	90	7.4
			100	9.6
			110	11.0
		1000	90	8.5
			100	11.4
			110	13.2
		1500	90	9.6
			100	13.4
			110	15.0
		2000	90	10.7
			100	14.6
			110	16
	2.4	500	90	10.5
			100	16.7
			110	19.3
		1000	90	13.3
			100	17.5
			110	19.6
		1500	90	16.3
			100	19.3
			110	20.6
		2000	90	17.5
			100	20.6
			110	21.6

Table F.1: Experimental Results for Heat Weld Strength Attachment on Hardwood Paper with Thickness of 0.1 mm

Appendix G-Experimental Results for Heat Weld Strength Attachment on Hardwood Paper with Thickness of 0.18 mm.

Paper Thickness (mm)	Contact Diameter (mm)	Force (gf)	Temperature (°C)	Mean Failure Force (N)
0.1	1.2	500	90	2.1
			100	5.3
			110	7.2
		1000	90	4.0
			100	6.6
			110	8.2
		1500	90	4.5
			100	7.6
			110	8.8
		2000	90	5.4
			100	8.8
			110	9.4
	1.8	500	90	5.9
			100	8.5
			110	11.3
		1000	90	6.8
			100	10
			110	12.9
		1500	90	8.2
			100	11.3
			110	13.5
		2000	90	9.6
			100	12.4
			110	14.5
	2.4	500	90	8.1
			100	14.1
			110	16.2
		1000	90	22.1
			100	10.4
			110	15.4
		1500	90	16.9
			100	23.3
			110	12.3
		2000	90	16.3
			100	17.6
			110	24.7

Table G.1: Experimental Results for Heat Weld Strength Attachment on Hardwood Paper with Thickness of 0.18 mm

Appendix H-Arduino Code for Scale Test

```
#include <ax12.h>
#include <BioloidController.h>
#include <XBee.h>

//Need to use 2 bytes for higher precision
//High byte *256 + low byte then construct in arduino to get the angle in float
//then figure out how to map float to int

int incomingByte = 0;    // for incoming serial data
BioloidController bioloid = BioloidController(1000000);

float shldr_Goal, elbow_Goal, wrist_Goal;
int shldr_GoalMap, elbow_GoalMap;

int up=640, down=497;

int high, low;

int presentelb, presentshldr, presentwrist;

char shldrChannel=1, elbowChannel=0, serialChar=0;

void setup() {
  Serial.begin(38400);    // opens serial port, sets data rate to 9600 bps

  //Get a response from the motors
  Serial.print(ax12GetRegister(1, 3, 1));
  Serial.print(ax12GetRegister(2, 3, 1));
  Serial.println(ax12GetRegister(3, 3, 1));  delay(100);

  //Set Arm to 0 degrees
  elbow_Goal = 600;
  shldr_Goal = 900;

  wrist_move(up);
  //sweep();

  Serial.print("ShldrGoal");  Serial.print("\t");
  Serial.print("ElbowGoal");  Serial.print("\t");
  Serial.print("WristGoal");  Serial.print("\t");
  Serial.print("Present deg pos");Serial.print("\t");
  Serial.println("Present pos");

  shldr_GoalMap=1922;
  elbow_GoalMap=348;
  delay(100);
  sweep();
  wrist_move(down);  delay(5000);
  wrist_move(up);
  feedback();
```

```
  printresults();
}
void loop() {
}

void sweep(){

  feedback();

  int elb_pos;
  int shldr_pos;

  if(presentshldr >=0) shldr_pos=presentshldr;
  else  feedback();
  if(presentelb >=0) elb_pos=presentelb;
  else feedback();

  //shldr_GoalMap= map(shldr_Goal, 0, 1800, 1024, 3072);
  //elbow_GoalMap=int( elbow_Goal*512/1500);

  //1970 and 350
  /*
  if(shldr_GoalMap >= 1485) shldr_GoalMap += 8;
  if(shldr_GoalMap >= 1439 && shldr_GoalMap < 1485)  shldr_GoalMap += 16;
  if(shldr_GoalMap ==1268) shldr_GoalMap -= 4;
  if(elbow_GoalMap == 122) elbow_GoalMap += 6;
  */
  //Check if you need to sweep forward or backward
  if(elbow_GoalMap > elb_pos)
  {  for(elb_pos = presentelb; elb_pos < elbow_GoalMap; elb_pos += 5)  // goes from 0 degrees to 180
degrees
    { SetPosition(2, elb_pos);            // in steps of 1 degree tell the servo to go to position in variable 'pos'
      delay(30);                       // waits 15ms for the servo to reach the position
    }
  }
 else if(elbow_GoalMap < elb_pos)
  {  for(elb_pos= presentelb; elb_pos > elbow_GoalMap; elb_pos-= 5)
    { SetPosition(2, elb_pos);
      delay(30);
    }
  }
  SetPosition(2, elbow_GoalMap);

  //Check if you need to sweep forward or backward
    if(shldr_GoalMap > shldr_pos)
  {  for(shldr_pos = presentshldr; shldr_pos < shldr_GoalMap; shldr_pos += 10)  // goes from 0 degrees to
180 degrees
    { SetPosition(1, shldr_pos);       // in steps of 1 degree tell the servo to go to position in variable 'pos'
      delay(30);                       // waits 15ms for the servo to reach the position
    }
  }
 else if(shldr_GoalMap < shldr_pos)
  {  for(shldr_pos = presentshldr; shldr_pos > shldr_GoalMap; shldr_pos-= 10)
```

```
    { SetPosition(1, shldr_pos);
      delay(30);
    }
  }
  SetPosition(1, shldr_GoalMap);  delay(200);
}

void wrist_move(float wrist_Goal){
  int wrist_pos;

  presentwrist = ax12GetRegister(3, 36, 2);

  if(presentwrist > 0) wrist_pos = presentwrist;
  else presentwrist = ax12GetRegister(3, 36, 2);

  if(presentwrist > 0) wrist_pos = presentwrist;
  else presentwrist=520;

  if(wrist_Goal > wrist_pos)
{  for(wrist_pos = presentwrist; wrist_pos < wrist_Goal; wrist_pos += 2)  // goes from 0 degrees to 180
degrees
    { SetPosition(3, wrist_pos);       // in steps of 1 degree tell the servo to go to position in variable 'pos'
      delay(45);                       // waits 15ms for the servo to reach the position
    }
}
  else if(wrist_Goal < wrist_pos)
{  for(wrist_pos = presentwrist; wrist_pos > wrist_Goal; wrist_pos -= 5)
    {
      SetPosition(3, wrist_pos);
      delay(30);
    }
}
  SetPosition(3, wrist_Goal);
  presentwrist=wrist_Goal;
  delay(100);
}

void feedback(){
  //Reading a packet of length 2 from 36 is the same as combining a high byte
  //from 37 and a low byte from 36
  presentshldr = ax12GetRegister(1, 36, 2);
  presentelb = ax12GetRegister(2, 36, 2);
}

void printresults(){

  //Serial.print( shldr_Goal/10);   Serial.print("\t");
  Serial.print( shldr_GoalMap);   Serial.print("\t");
  //Serial.print( elbow_Goal/10);   Serial.print("\t");
  Serial.print( elbow_GoalMap);   Serial.print("\t");
  Serial.print( presentwrist);    Serial.print("\t \t");

  Serial.print( float (map(presentshldr, 1024, 3072, 0, 1800))/10 );
```

```
  Serial.print("\t \t");
  Serial.println(presentshldr);   Serial.print("\t \t \t \t \t \t");

  Serial.print( float (map(presentelb, 0, 512, 0, 1500))/10 );
  Serial.print("\t \t");
  Serial.println(presentelb);
}
```

Appendix I-Linear Actuator Platform Drawing

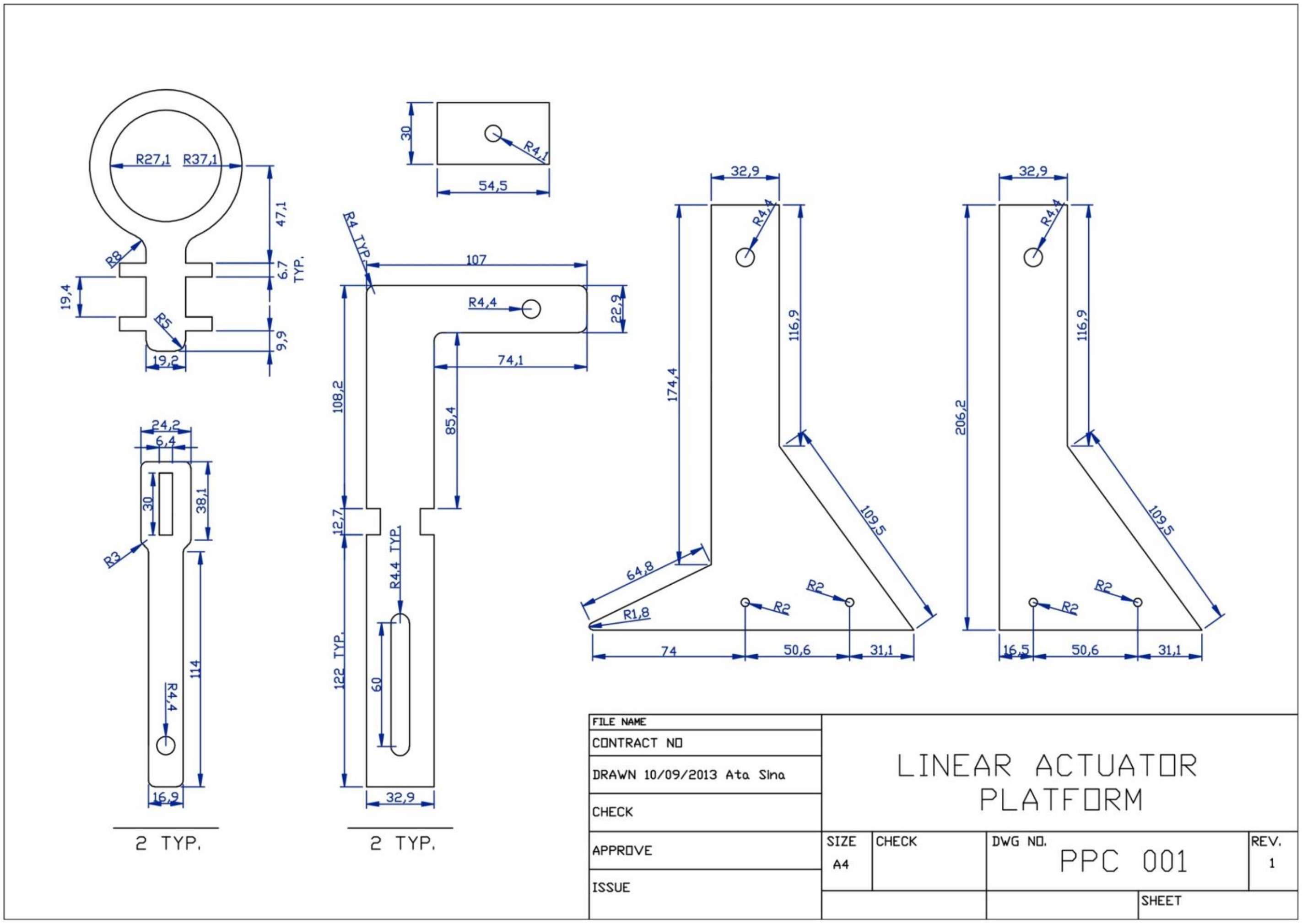

Figure I.1: Linear actuator platform drawing

Appendix J-Robotic Arm Design to Automate Bonding

The second step in the autonomous paper origami procedure is to create an automated system to attach plastic material to the paper at desired points by using heat and pressure. A few design paths were considered to solve this problem.

One option is a printer-like design with the plane degrees of freedom (DOF) controlled separately, which is easier to control yet more difficult to build and design mechanically. Rollers, gears, couplings and other mechanical parts required to make it work would have to be purchased or machined, potentially taking more time than necessary. The ability to model, dimension and build the parts without error was needed. Consequently, it was implausible to proceed with this design.

The second option was to build a robotic arm. From rotating servo motors, the end effector would move through two degrees of freedom simultaneously but would be easier to build with off-the-shelf parts. Having some experience with Arduino and servo motors also made this a more plausible option. Mechanical simplicity outweighed program simplicity and so this design path was chosen.

Inspiration was taken from a hobbyist who posted a video on YouTube, called "Paul the Robot[1]", which was a programmed robotic arm using servo motors to draw a portrait on an A4 sized paper. Using this idea, it was conceivable to imagine the same robot could be used to make plastic connections to an A4 sized paper, replacing the pencil with a soldering iron instead.

The servos are programmed with a pulse width modulation (PWM) output from a microcontroller to adjust the positions. The microcontroller used would be one of Arduino's, which would allow open source forums to take advantage of it.

To introduce Arduino, it is an open source programming software that allows users to write code with an easy to understand form of C++ coding. Many users have created their own libraries and freely posted their code for Arduino controllers. Using this powerful framework, code from other users with similar projects could be accessed and troubleshooting coding problems would be much easier due to the large number of Arduino users.

Having known about Arduino software, and servo interfacing with the Arduino Uno microcontroller, this was used as a starting point for the design. By using two degrees of freedom (DOF) for the arm, it was fairly simple to map coordinates to angles using inverse kinematics. By using the PWM pins on the microcontroller, the servos would respond to the duty cycle of a digital square wave output. This was encapsulated by libraries already designed by the Arduino community.

A proof-of-concept design was created to show how easily servo motors could be controlled using an Arduino Uno microcontroller.

1 URL to "Paul the Robot", https://www.youtube.com/watch?v=bbdQbyff_Sk, 2013

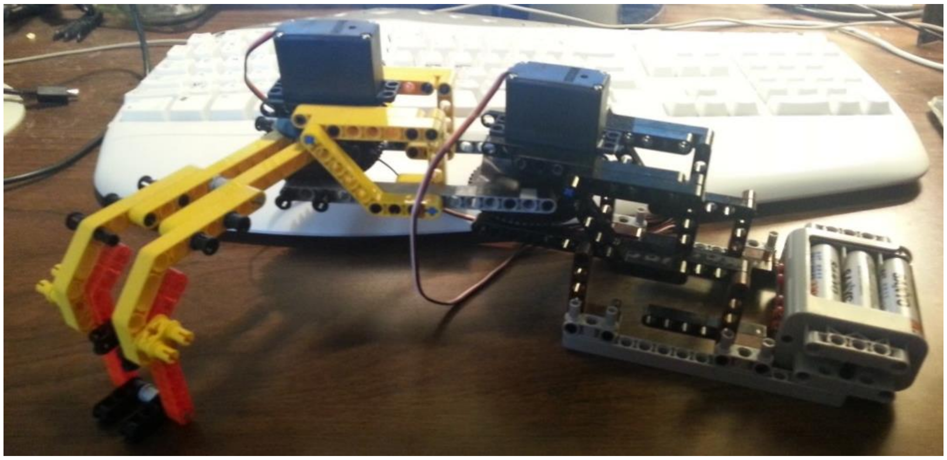

Figure J.1: First prototype of the robotic arm using lego

After further research, robotics suppliers and manufacturers who specialize in building rovers and robotic arms were discovered. Lynxmotion and Robotshop were a great source of easy-to-assemble aluminum parts that screw directly on the servos. Using a few U-shaped brackets a design similar to "Paul the Robot", was constructed.

A coordinate system was put in place as a reference for the robotic arm. By placing the plastic and paper on the coordinate system, the points of connections would be referenced and inputted into a notepad file to be read by the program. Using an inverse kinematics calculation, the points would be converted into angles for the servo motors. Botboarduino, another Arduino compatible microcontroller, is specifically designed for controlling servos. This hardware was chosen for the design because it works as both microcontroller and motor driver, meaning, it can output a higher current to the servo motors where a conventional microcontroller would fail. Also, since the servos directly plug into the microcontroller the need for an exterior power regulating circuit is eliminated.

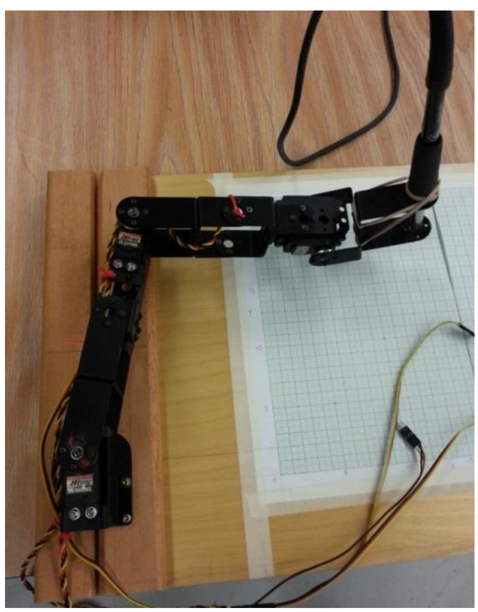

Figure J.2: Second prototype of the robotic Arm using parts from Lynxmotion

Being met with accuracy problems, further research was done to see if there were more accurate, powerful motors on the market. Eventually, Robotics motors were found with extraordinary capabilities beyond the common servo motors. Titled as a robotic actuator, this motor used TTL logic and data registers to control and monitor all the parameters of the motor without making programming more difficult.

AX-12 and MX-12 motors with twice the torque, and five times the capabilities of the strongest servo motors were bought. The angle precision is rated for two tenths of a degree for the AX motor and eight hundredths of a degree for the MX motors.

Comparatively, conventional servos have a rating for a precision of one or two degrees. By multiplying the angle by the radial arm, it was discovered that we would be able to achieve two millimeters of accuracy at best without considering other contributing factors of inaccuracies.

Part	Supplier	Quantity
Arbotix Microcontroller	Trossen Robotics	1
Xbee	Trossen Robotics	2
MX-12 Robotic Actuator	Trossen Robotics	2
AX-12 Robotic Actuator	Trossen Robotics	1
C-Brackets	Trossen Robotics	6

Table J.1: The list of servo-robot parts

In order to reduce the amount of calculations performed by the microcontroller, and have the function of reading a text file, a computer application was written in addition to the microcontroller code. The computer application read the text file and performed the inverse kinematics calculation. It was written using Processing, an Arduino compatible software exclusively for computer-microcontroller interfacing and applications.

Once completed, it would wireless transmit the angles to the microcontroller via radio with the Xbee. The microcontroller would then receive this data, sweep to that angle and give feedback of its current position. Using this structure it was easy to isolate each function and debug the program accordingly. Using the feedback capabilities of the motor, the accuracy problems could be debugged more easily. The Arbotix microcontroller code is shown with comments in Appendix A and the Processing application code is given in Appendix D.

Testing the Accuracy

A major issue in the designing of the robot has been to perform the task with high accuracy. The inexpensive servo motors purchased had low accuracy and no feedback control. The tolerance for the servo motor would be as high as five degrees and with a long arm to accentuate this, the error was significant.

The goal was to produce a tolerance of about two millimeters in both planar axes. This is on a scale of approximately one hundredth of degree accuracy from the servo. After doing some research the servos were switched to robotic actuators manufactured by Robotis.

The actuators from Robotis came with a design specification of 0.08 degree accuracy. To add to that, the motors had feedback control capabilities, allowing the position, torque and velocity to be monitored and controlled along with a number of other parameters.

While the electronic equipment along with the software went through several improvements, the mechanical imperfections were still preventing the necessary accuracy. Vibration, alignment and accurate dimensioning of the arm proved to be another source of inaccuracies.

Knowing this, a few steps were taken to try and rectify this. Firstly, many measurements were done to try to get the specific arm lengths and distance from the origin for accuracy movements. A MATLAB code was then created to reverse calculate all the lengths using specific coordinates with their corresponding angles.

Once no further improvement could be reached using this method, a 3D map of the error was plotted with Microsoft Excel by moving the arm manually to each position and reading the angles. By changing the lengths, the excel map would show what the distance error would be. This was used to attempt to minimize the error but also could not fully remedy the problem.

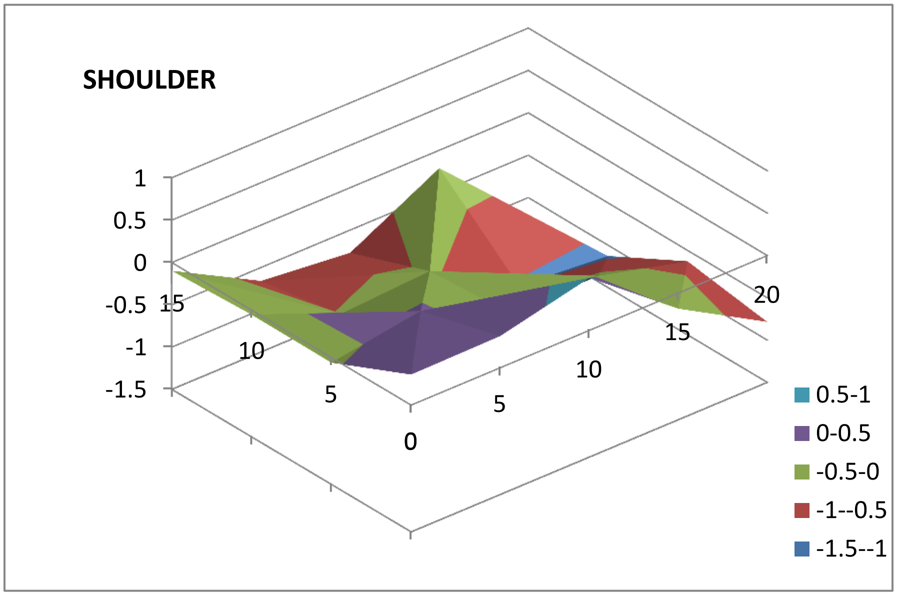

Figure J.3: 3D map of the servo-robot shoulder's error

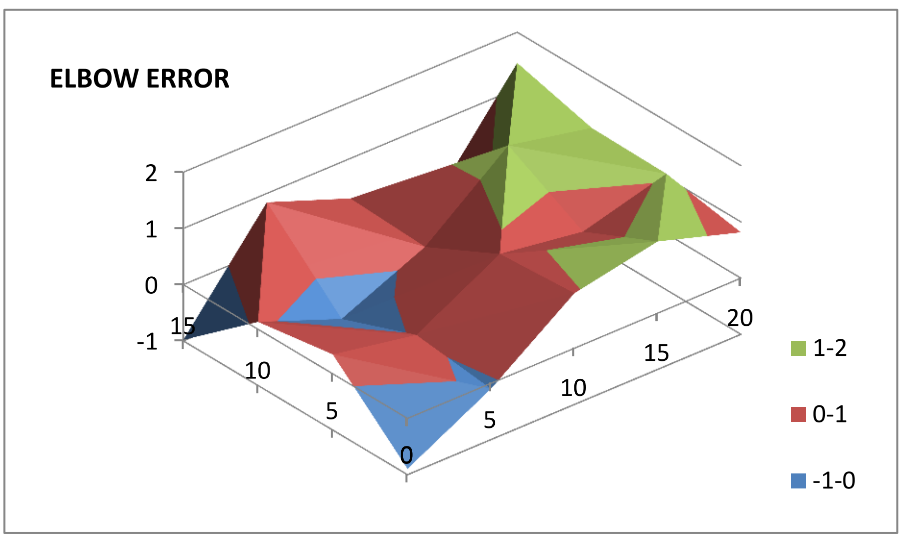

Figure J.4: 3D map of the servo-robot elbow's error

During the testing stages it was apparent that the limitation of the servo accuracy would make this device unusable for this application. Different models of Hitec, JR and Robotis servos were tested and all proved to be too inaccurate due to the large arm radius amplifying the error. Also, due to other mechanical problems such as rigidity, vibration and deflection, the robot was not predictable enough.

If highly accurate linear actuators, or stepper motors from other suppliers were used, we would be able to achieve within millimeters of the tolerance accuracy. After some further research a number of accurate actuated printers were discovered for reasonable prices.